FLIGHT AND ENGINES

BY

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PREFACE

This book is written for the reader who desires a sound knowledge of the basic principles governing the flight of the aeroplane and the operation of its engine. It is written without constant reference to mathematics; nevertheless, every endeavour has been made to achieve precision of thought and expression, a feature occasionally lacking in books of this kind.

It has been the special aim of the author to meet the needs of the A.T.C. and the cadet in the early stages of his training, and it is hoped that such readers will find the book readable as well as reliable.

Trouble has been taken to explain as thoroughly as space permits those parts of the subject that sometimes prove puzzling, and since much that is known about the aeroplane is better taught by pictures, the book is liberally illustrated.

A number of questions are added to the end of each chapter, and should prove particularly useful to those readers who are studying the subject with an examination in view.

G. V. W.

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Read by Abdul Gani Dar F.Sc student
A.S. College Srinagar Kashmir.
(Note.) It is good book for those
people who want to join in ~~K.J.A.F.~~
(Royal Indian Air Force.)

Part I—PRINCIPLES OF FLIGHT

CHAPTER I

How the Wings Support the Aircraft

INTRODUCTION. FUNCTION OF THE WINGS. THE VENTURI EFFECT. HOW THE WING GETS ITS LIFT. PRESSURE DISTRIBUTION ABOUT THE WING. ANGLE OF ATTACK. PRESSURE DISTRIBUTION AND ANGLE OF ATTACK. TOTAL REACTION. LIFT AND DRAG. THE FIVE FACTORS ON WHICH LIFT AND DRAG DEPEND. STALLING OF A WING. CONNEXION BETWEEN STALLING ANGLE OF THE WING AND STALLING SPEED OF THE AIRCRAFT. MOVEMENT OF THE CENTRE OF PRESSURE WITH ALTERATION OF THE ANGLE OF ATTACK. CHARACTER OF STALL: BIPLANES AND MONOPLANES FACTORS UPON WHICH STALLING SPEED DEPENDS IN STRAIGHT AND LEVEL FLIGHT. WING LOADING.

Introduction.

When men thought that the earth was flat, explorers must have dreamed with feelings of exhilaration and excitement of limitless travel. The realization that the human race lived on a spherical world must surely have brought, to philosopher and explorer alike, a sense of disappointment and frustration, for the boundaries of their existence were clearly defined: travel could be endless—but unlimited? No! Men and women must be content to crawl upon the surface of one of the smaller planets in a somewhat insignificant group of dead stars amongst billions of greater worlds.

At no time could this sense of confinement have weighed more heavily upon man's eager mind than whilst watching the graceful and seemingly effortless flight of birds. Here, at least, was one living creature able to defy, for however short a time, the clutch of gravity. Even though a thin blanket of air put an invisible wall around the earth, birds were like beings released into a garden, whilst men, the pride of all creation, must watch from prison bars.

The legend of Icarus must ever symbolize man's dreams of flight. His tireless efforts to attain the freedom of a third dimension compose a saga of courage and imagination. For centuries the secret of powered flight seemed almost within his grasp. Birds, insects, and even seeds were able to use the mysterious forces of the invisible air to carry them from place to place. Surely man could imitate them?

It was this very imitation of the flight of birds that so long delayed his mastery of the air, for all attempts to fly with flapping wings failed, not from any error in fundamental principles, but because men's muscles and bony structure are ill adapted for the operation of wings. Neither was it realized in those early days that the supporting and stabilizing surfaces must be carefully positioned with respect to the weight to be supported.

For many centuries no careful scientific experiments were conducted. It was a long time, too, before man realized that great skill would be needed to operate a flying machine. With the passage of time knowledge increased. Leonardo da Vinci's theories, Sir George Cayley's experiments, Stringfellow's and Langley's models, and Lilienthal's gliders culminated in the powered aircraft of Wilbur and Orville Wright which made the first man-carrying flight of history in 1903.

Through the work of these men and hundreds of others there has emerged the knowledge of the fundamental principles underlying heavier-than-air flight.

The would-be flyer of the modern world is fortunate in being able to begin where others have left off. Even so, he too must master the fundamentals before he may presume to solve the complex problems set by the modern aircraft in flight. He must try from the beginning of his training as a member of an air-crew to think clearly and talk correctly about flying matters. The best practice is built only from the soundest theory. Faulty explanations and loose reasoning are not only no help, but may constitute a real danger.

It must be remembered that flying to-day is no matter of mere circuits and landings on a fine day, or of following railway lines in a slow aircraft. Flying means aerobatics, instrument flying with no visibility, at night and often in hazardous weather; it means navigation, radio, formation flying, and tactics. Even the most brilliant mathematician began by learning to add, subtract, multiply and divide: the most gifted flyer must know first the fundamental principles of flight.

Function of the Wings.

In order that an aircraft may fly, it must be supported in the air. The airflow over and under the wings, due to their motion through the air, produces an upward force, counteracting the weight of the aircraft, and thus supporting it.

Sometimes it is better to think of the aircraft as moving through the air, and sometimes of the air as moving past the aircraft, as it does when a model aircraft is placed before a wind-tunnel. It really

matters little which way it is thought of; it is the relative motion that counts. When the pilot flies the aircraft, there is an airflow over the wings relative to the aircraft and created by its motion through the air. It produces the same effect as if the aircraft were motionless and the airflow were created by some other means such as a wind-tunnel. In the same way a cyclist, even on a calm day, must always push his way through the air against a wind of his own creating, no matter which way he turns. This airflow is usually called the *Relative Wind*, but it must be noted that it has nothing to do with the ordinary

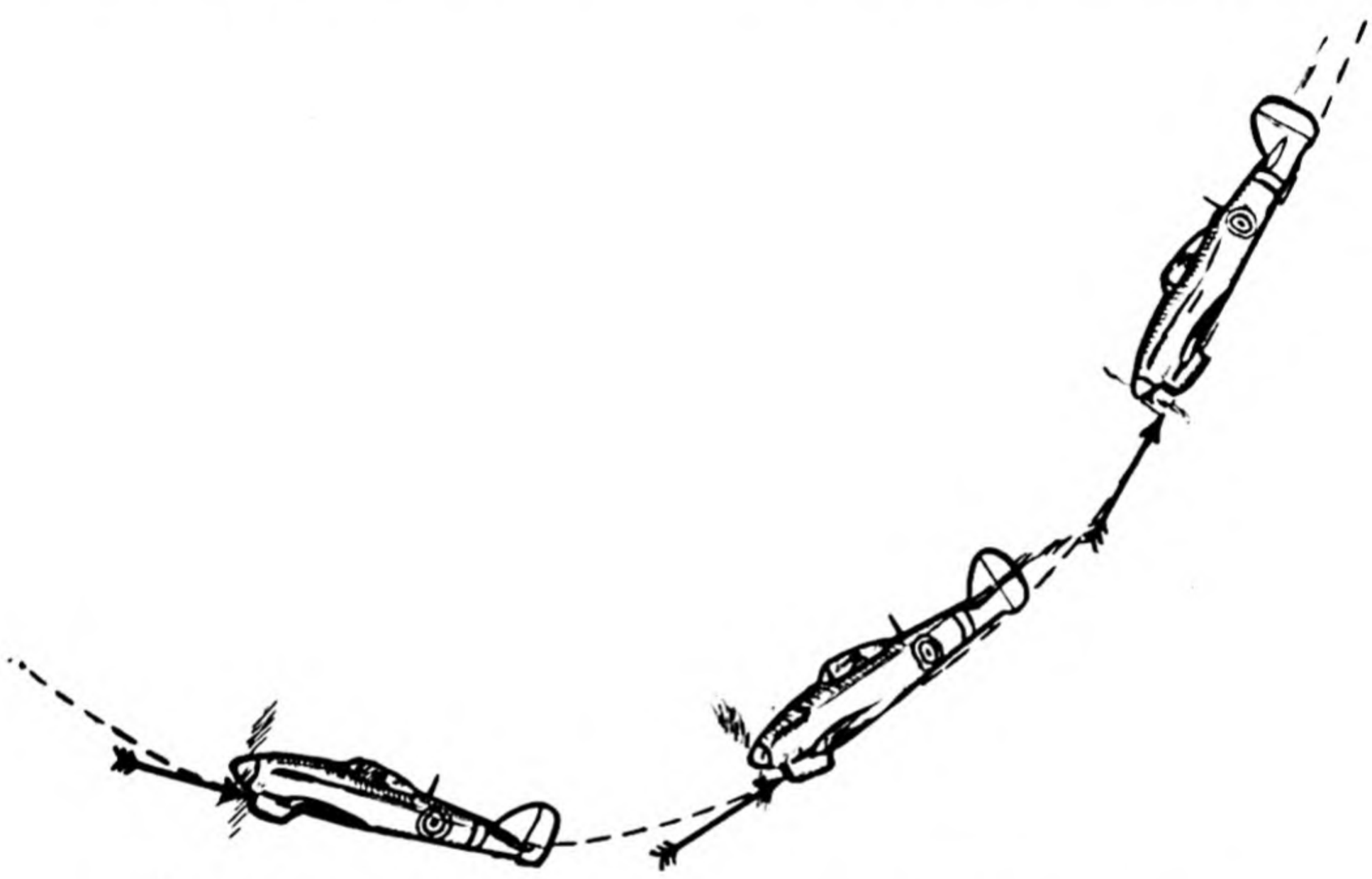


Fig. 1.—Relative wind is created by the motion of the aircraft through the air

winds that the meteorological officer gives to the navigator. As far as handling the aircraft is concerned, these mass movements of the air in which the aircraft flies may be forgotten, for the aircraft moves with them. If they are steady they have no effect on the way in which the pilot flies his machine.

Since this relative wind is created by the aircraft's own speed through the air that surrounds it, it is always, as shown in fig. 1, a "head wind". It strikes the wings in a direction which lies along the line of motion and is, in fact, the direction of motion of the aircraft reversed. If a small flag were fixed above the fuselage of the aircraft, it would always blow straight back along the centre line of the aircraft in steady flight. A pilot who lifts his head beyond the protection of his cockpit cover will always feel the "wind in his face", and no matter how hard the gale drives the rain for people on

the ground, it will never beat on the side of the aircraft in the air. This, of course, is due to the fact that the aircraft is carried along with the wind and the rain, and drifts just as fast as, and no faster than, the air mass surrounding it, and in the same direction.

In all theorizing about flight, therefore, we can, as far as actual flying is involved, think only of the relative wind, or airflow. The effect of the wind in steady flight need only be considered when motion relative to the ground is our concern.

The Venturi Effect.

In order to understand how this airflow over the wings of an aircraft produces the required lift, it is first necessary to consider an interesting and somewhat surprising physical effect produced whenever a fluid, whether liquid or gas, flows smoothly through a constriction.

Imagine water flowing through a pipe that is narrower at one point than at another. It is clear that the same amount of water must pass in unit time through the narrow part as through the wider part unless there is a leak, for there is nowhere else for it to go. This

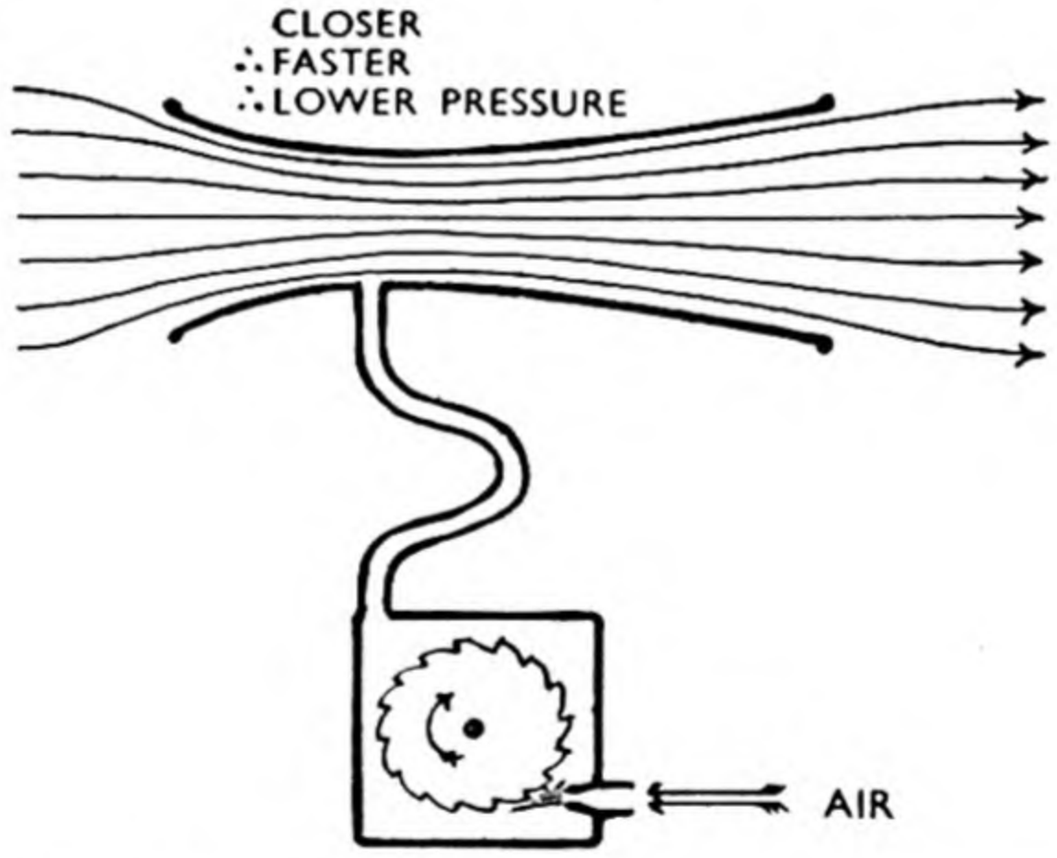


Fig. 2.—Action of a Venturi tube when used to drive a gyro-operated aircraft instrument

implies a faster rate of flow through the smaller cross-section of the narrow part of the pipe. What can have given the water its increased speed? It must have obtained the energy for this extra motion from somewhere, for energy cannot be conjured out of nothing. The source of this energy is to be found in the pressure exerted by the fluid upon the walls of the pipe, so that when the water accelerates, it is at the expense of the pressure. The pressure is therefore found to be somewhat less in the constriction than in the wider part of the

tube. At first sight it would seem that the fluid should be " squashed up " in the narrow part, but experiment clearly demonstrates that this is not so, and that the drop in pressure does actually exist. This is known as the Venturi principle.

There is a Venturi tube on the outside of many aircraft, though it has nothing directly to do with keeping it in the air. It provides the motive power for some of the instruments on the instrument panel. The arrangement is shown in simplified form in fig. 2. The reduction of pressure in the constriction draws air through the tube connected to it, so causing the jet of air that drives the gyrostats upon which the artificial horizon, direction indicator, and turn-and-bank indicator depend for their operation. The same principle may be seen at work when two boats are moored near each other in a stream. The flow of water between them causes a reduction of water pressure at that place, and the boats are drawn together, as in fig. 3. The principle finds an application in the ordinary scent-spray, in which a reduction of pressure sufficient to draw the liquid from the bottle is obtained by forcing air through the constricted orifice of a narrow tube.

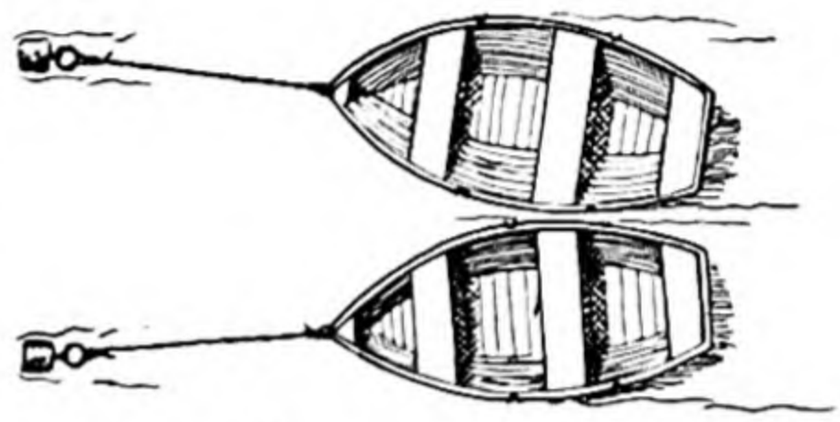


Fig. 3.—Boats drawn together by Venturi action

In fact, without labouring the point further, it may be stated that *wherever the lines of flow of a fluid become closer, the fluid will travel faster, and wherever it travels faster, there will be a reduction of pressure.* The reverse is also true: wherever the lines of flow are farther apart, rate of flow will decrease, and there will be a rise in fluid pressure.

How the Wing gets its Lift.

If a flat piece of card is held in the airflow from a wind-tunnel with its leading edge slightly raised from the horizontal position, it experiences an upward force. If the lines of airflow (usually called streamlines) were visible, it would be noticed that they are closer together over the upper surface and farther apart underneath. On top of the card two things are happening: the air is travelling faster, and, in consequence, the pressure is reduced. At the lower surface the opposite occurs. In fact, the lift that the card experiences might be explained by saying that it is being sucked from above and pushed from below, but a better way of saying this is to speak of the lift as due to the *difference* of pressure between the top and bottom of the card. In still air, pressure on the card is the same on the top as on the bottom, and the forces are balanced. When the airflow is lifting

the card, the pressure forces are unbalanced: the push from beneath is increased, whilst the push downwards from above is decreased. The difference between these two leaves an unbalanced force acting upwards.

Experiment has shown that greater lift can be obtained by using a " cambered " surface, i.e. one with a slightly curved centre line, convex side upwards. This and other considerations have led to the type of wing with which most people are now familiar.

The aircraft wing and a Venturi tube depend on identical principles for the effects they produce (fig. 4). The upper surface of a wing may be compared with half a Venturi tube of the usual kind, and the lower surface is similar to half a reversed Venturi. It is not difficult to devise a simple experiment to illustrate this. Two curved

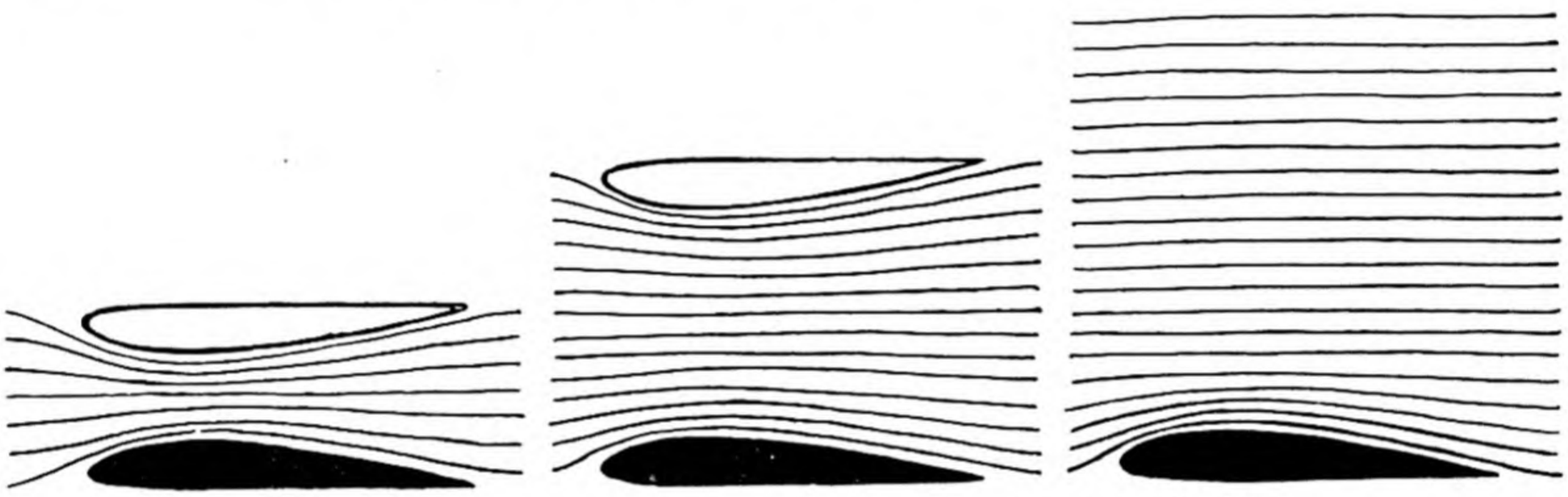


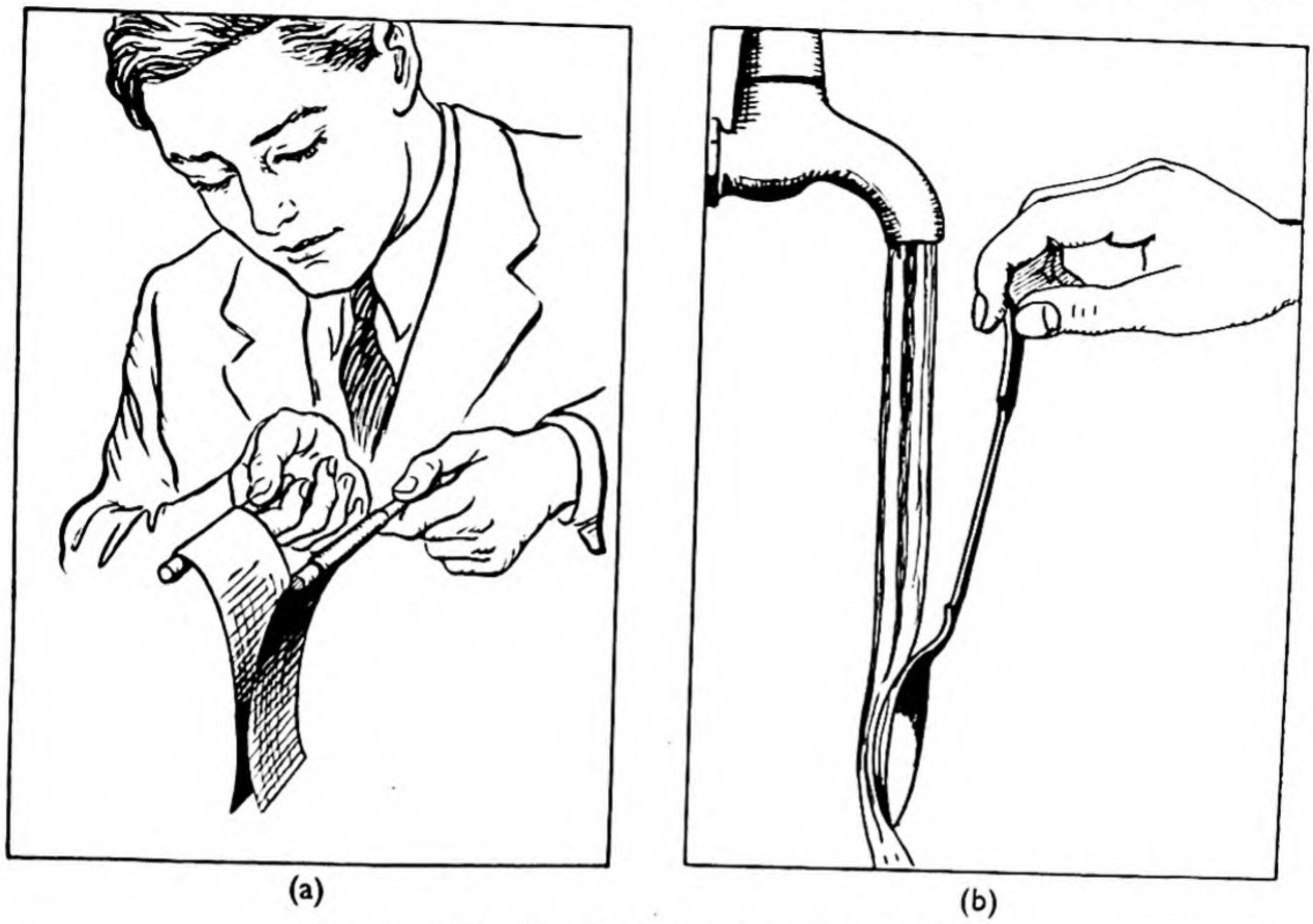
Fig. 4.—The Venturi tube and the wing use the same principle

sheets of stout paper swung freely from a pair of pencils are allowed to hang with their convex sides facing each other an inch or two apart (fig. 5*a*). On blowing through the gap between them the experimenter will find that the two sheets are drawn together. If one of the sheets only is used, blowing over the convex surface will again cause a pressure reduction on the convex side and the paper will swing in that direction. Another way of demonstrating the same thing demands only a table spoon and the kitchen sink. The back of the spoon is allowed to touch the side of a jet of water from the top. Instead of being pushed away, as might be expected, the spoon is drawn into the jet of water with some force (fig. 5*b*).

The airflow above and below the aircraft's wings is the secret of its flight. The diagram (fig. 6) is worth careful study. The following should be noted:

1. The upwash in front of the wing.
2. The downwash behind.
3. The part of the wing where the streamlines are closest.
4. The part of the wing where they are farthest apart.

The upwash makes it clear that the disturbance of the air at any point begins before the leading edge of the wing reaches it. The



(a) (b)

Figs. 5*a* and *b*.—Experiments illustrating Venturi effect

downwash shows that as the wing moves forward, air is continuously thrown downwards. According to the laws of mechanics, an upward

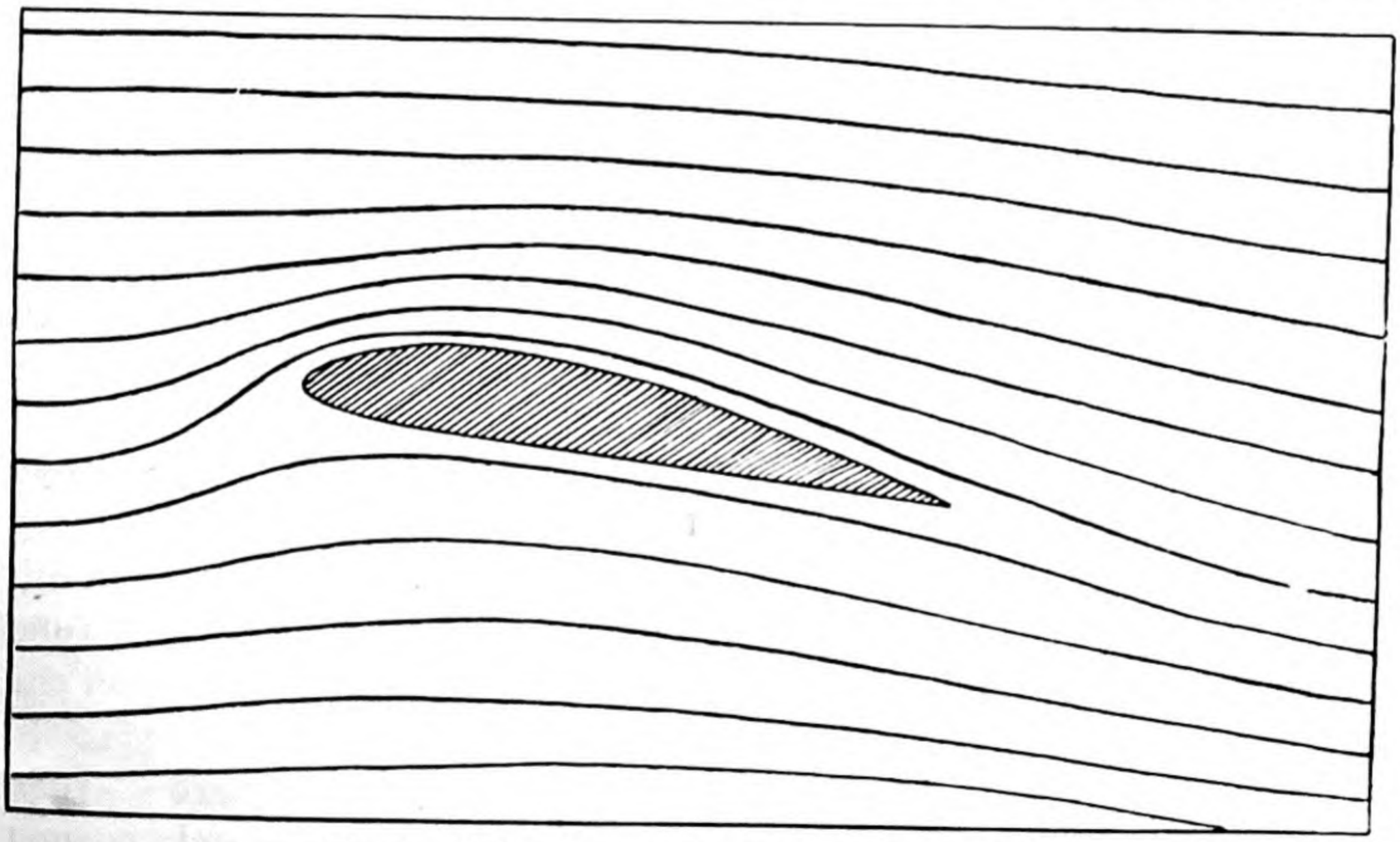


Fig. 6.—Airflow about a wing at normal angle of attack

force or reaction on the wing could not exist without this imparting of downward momentum to the air.

Pressure Distribution about the Wing.

The pressure reduction is not uniform over the upper surface, nor is the pressure increase constant over the bottom surface. The pressures can be measured, and, as would be expected, the greatest differences from normal pressure are to be found where the streamlines are closest and the air is moving fastest on top, or where the streamlines are farthest apart and the air is moving slowest underneath. In both cases this is near the leading edge.

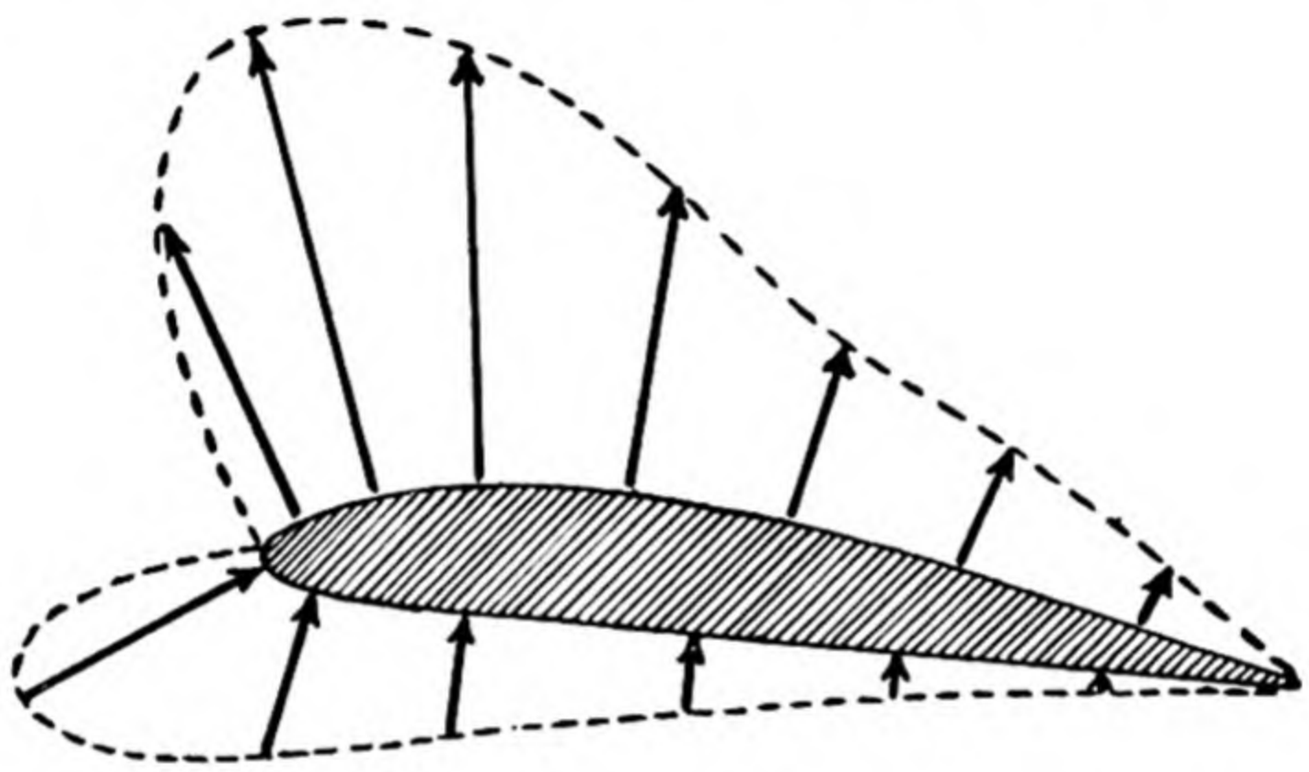


Fig. 7.—Pressure distribution about a wing in flight

Moreover (and this is very important), the average reduction of pressure is more than twice as great as the average increase of pressure on the lower surface. *It is the top of the wing that contributes the major portion of the lifting effect.*

Lastly, this reduction should never be referred to as a " vacuum ". If it were, then the heavy Stirling bomber would only need wings about 4 ft. × 5 ft. each. The actual reduction is very small, and averages about one hundredth of an atmosphere, whilst underneath the pressure is about one two-hundredth of an atmosphere above normal.

Normal atmospheric pressure near the ground is approximately equivalent to a force of 2000 lb. on any square foot. An average decrease of pressure on the upper surface of a wing of one hundredth of this reduces the force acting downwards to 2000 — 20 lb. = 1980 lb. An increase of one two-hundredth of the normal pressure on the under surface changes the upward force to 2000 + 10 lb. = 2010 lb. These two unbalanced forces leave a residual force of 2010 — 1980 lb. = 30 lb. acting upwards. These figures are approximately correct

for a Spitfire fighter's wings, each square foot of which supports about 30 lb. weight. The wings are of such a size that, when all the square feet of wing area are added together, enough support is provided to lift the whole aircraft into the air.

Of course, this simple calculation is based on the assumption of mean or average pressure alterations on each of the two wing surfaces, and it has been emphasized that, as a matter of fact, the pressure distribution is far from uniform.

If lines are drawn from points on the wing section at right angles to the surface at the point where they touch, to represent by their length the pressure at that place, then the diagram shown (fig. 7) is the result. The direction of the arrows shows whether there is a reduction or an increase in pressure.

Angle of Attack.

The attitude of the wing to the direction of motion or undisturbed airflow makes a considerable difference to the pressures at its surface. It is therefore necessary to have some reference line in the wing from which to measure changes in the attitude. The line chosen is *the line joining the trailing edge to the leading edge, and is called the chord.*

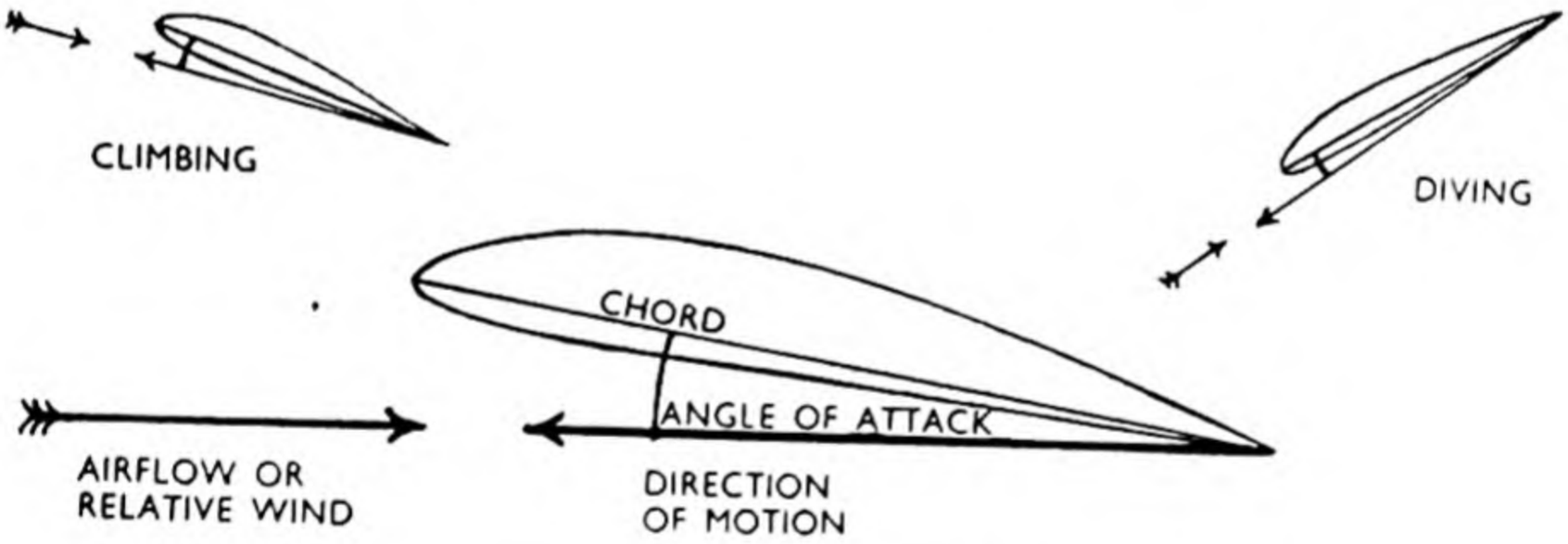


Fig. 8.—Angle of attack

In normal flight the leading edge is raised slightly and the chord makes an angle of 3° or 4° with the airflow or relative wind. This is called the angle of attack. *Thus the angle of attack may be defined as the acute angle between the chord and the relative wind.*

Note that the angle is *not* measured between the chord and the horizontal. A reference to fig. 8 will make it clear that it is the angle at which the wing meets the air that counts, and when the aircraft is climbing or diving the angle of attack is still a few degrees above the relative wind.

Pressure Distribution and Angle of Attack.

The diagram (fig. 7) shows the pressure distribution for an angle of attack of about 5°. The additional diagrams (fig. 9) show typical pressure distributions at other angles of attack.

At small negative angles of attack, when the chord is below the relative wind line, the sum total of the forces may be zero, and the wing will give no lift.

As the angle of attack grows, the upward forces grow too, but an angle of attack is reached at which the forces change quickly, and the reduction of pressure on top of the wing becomes suddenly smaller.

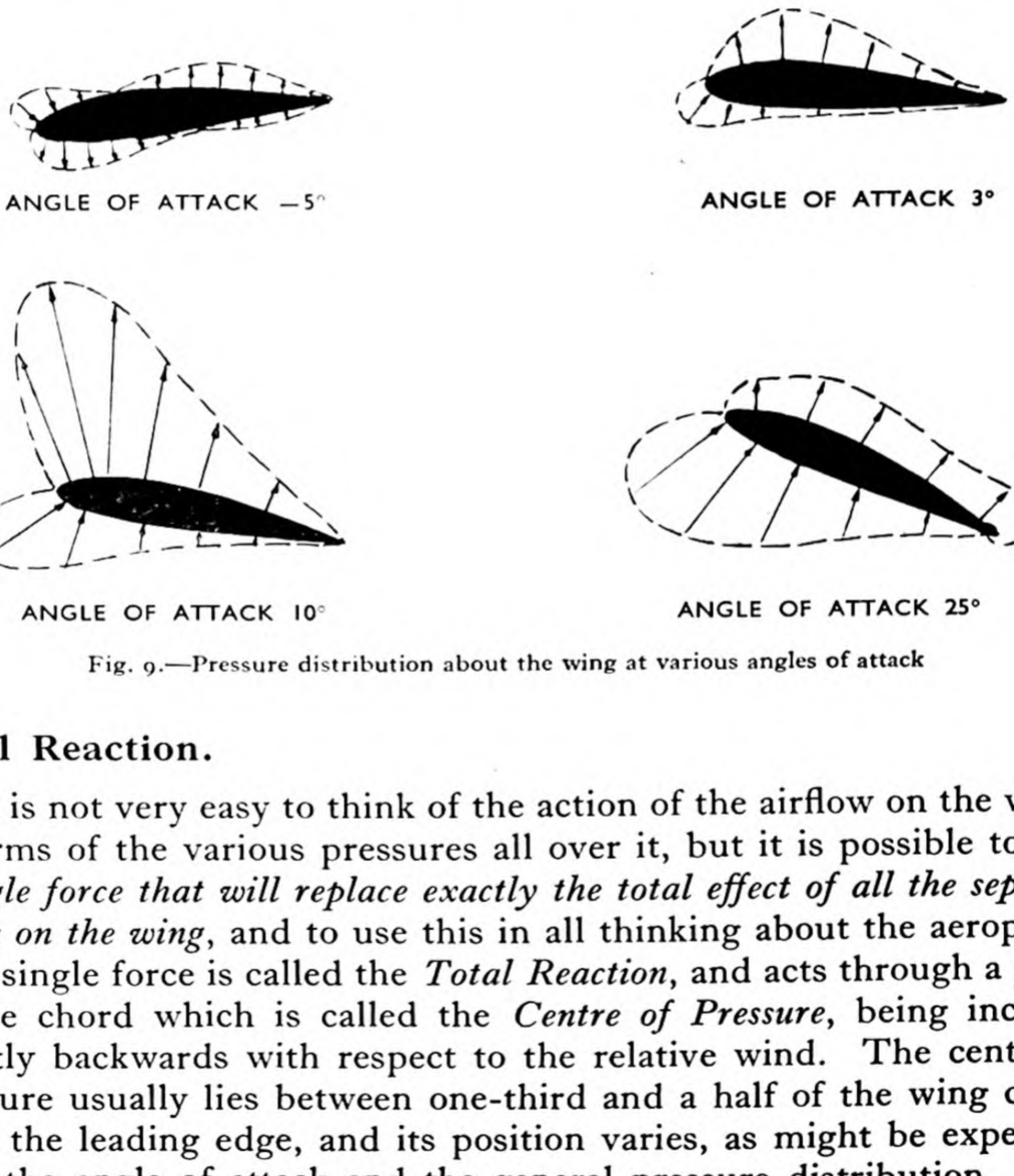


Fig. 9.—Pressure distribution about the wing at various angles of attack

Total Reaction.

It is not very easy to think of the action of the airflow on the wings in terms of the various pressures all over it, but it is possible to find a *single force that will replace exactly the total effect of all the separate forces on the wing*, and to use this in all thinking about the aeroplane. This single force is called the *Total Reaction*, and acts through a point in the chord which is called the *Centre of Pressure*, being inclined slightly backwards with respect to the relative wind. The centre of pressure usually lies between one-third and a half of the wing chord from the leading edge, and its position varies, as might be expected, with the angle of attack and the general pressure distribution. The size and direction of the total reaction also vary with the angle of attack, following the alteration in the pressure. At small angles of

attack the total reaction is small; it grows rapidly, and then decreases again, whilst inclining more and more backwards at large angles of attack.

Lift and Drag.

The result of the backward slope of the total reaction is that, whilst it has a lifting effect, there is also a dragging effect. This drag must be overcome by the thrust of the propeller.

In order to see clearly how much lift (which the designer wants) and how much drag (which the designer does not want) go to make up any particular total reaction, the total force is resolved, or split

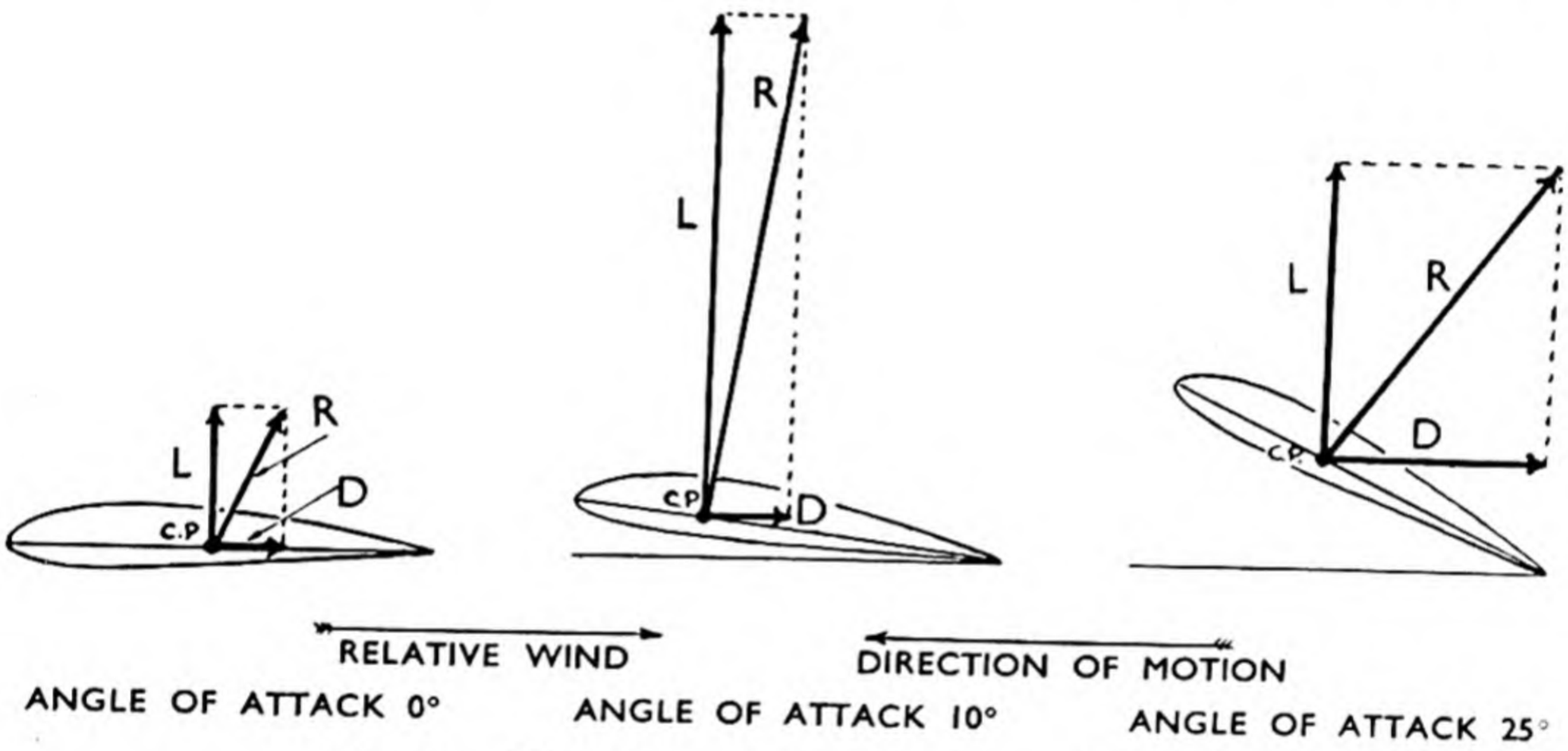


Fig. 10.—Lift and drag at three different angles of attack

up, into two parts which will have the same total effect. This is done by the application of the parallelogram of forces in the usual way, and the sizes of the two component forces relative to the resultant force that they have replaced are shown by the lengths of the lines in the diagram (fig. 10).

It must be clearly understood that a single force can be split into two forces in any two directions, but in this case the directions that are chosen are *parallel and perpendicular to the relative wind.* This means that only when the aircraft is flying horizontally is the lift vertical, and sometimes it may not be doing much lifting at all. There is nothing contradictory in this; it is merely due to the definition of lift that we have adopted. On the other hand, the drag is always acting backwards, resisting the motion of the aircraft through the air.

THE FIVE FACTORS ON WHICH LIFT AND DRAG DEPEND

The reader will be aware that wing shapes display almost as much variety as feminine headgear, yet the aircraft wearing them all seem to fly successfully. Moreover, a particular aircraft may use a range of speeds in level flight, and fly at widely different altitudes. In all these varied conditions the wings produce the lift necessary to keep the aircraft airborne. What, then, determines this lift?

Lift and drag, being both components of a single reaction, depend on the same factors. In order to study just how they vary, it is obviously necessary to consider each factor in turn, whilst the others remain constant.

1. *SHAPE.*

(*a*) *In Plan.* Wings that are long and narrow give a little more lift and a little less drag than those whose area is disposed differently by making them short and wide.

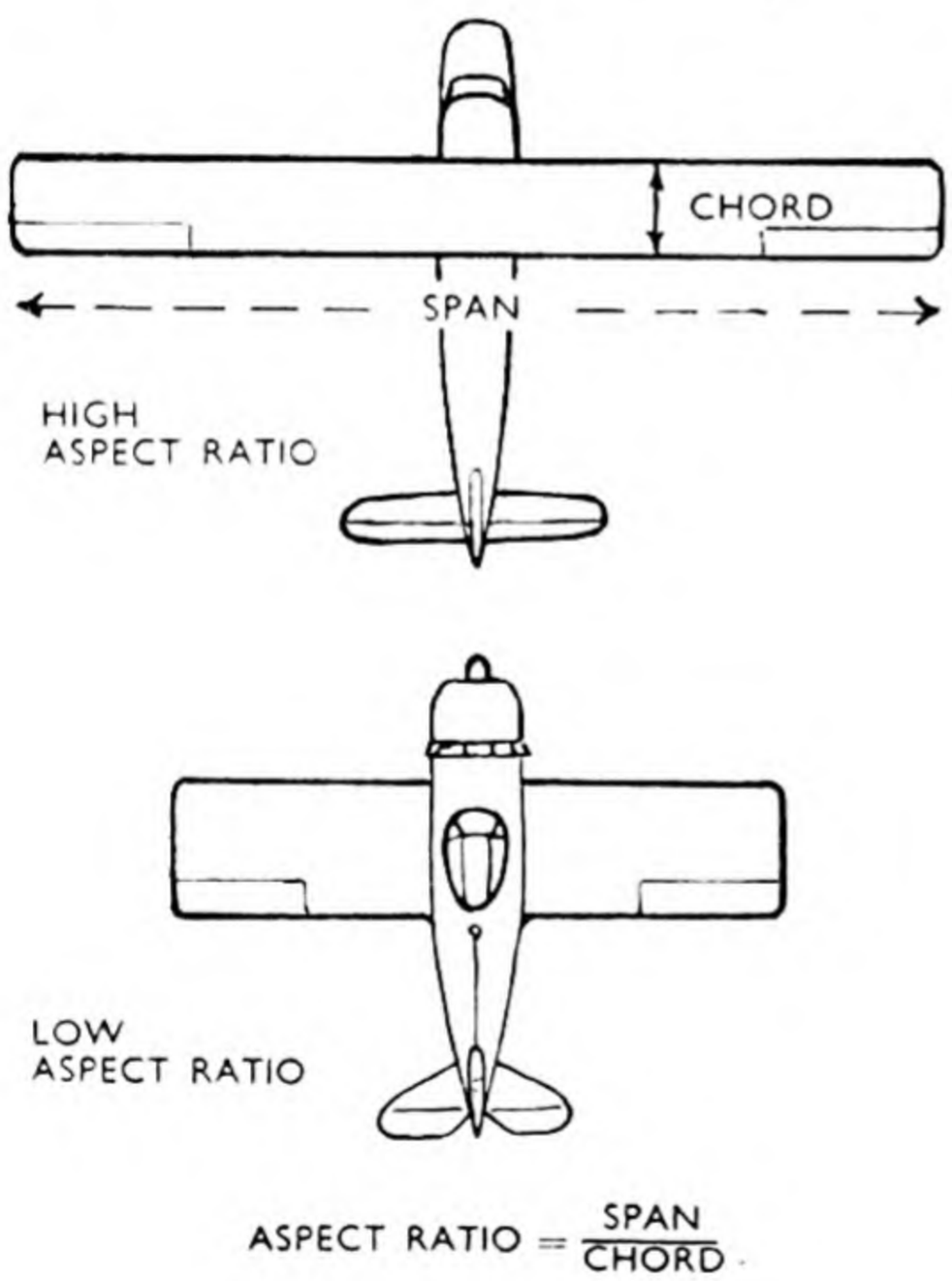


Fig. 11

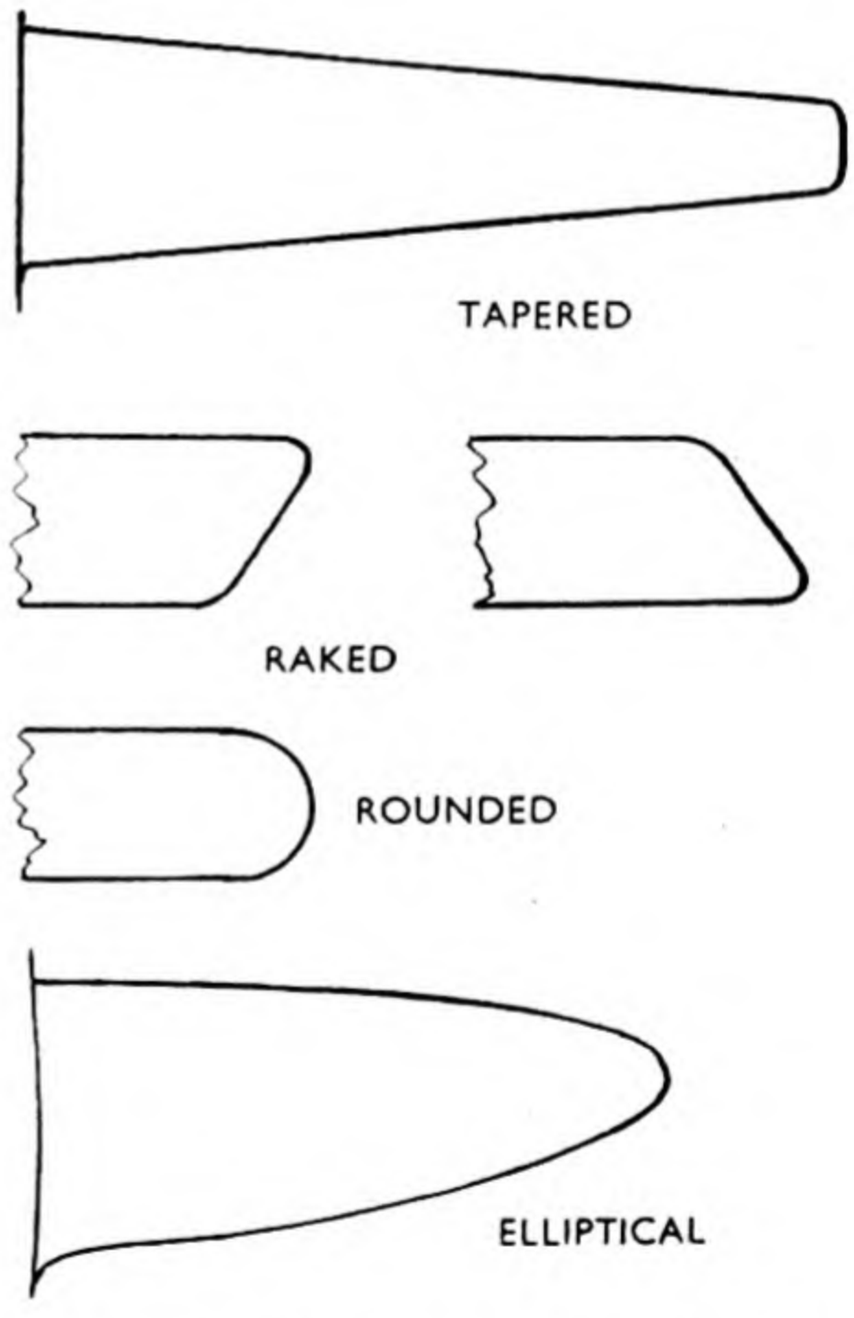


Fig. 12.—Variation in wing shape

The ratio of the span, that is the wing-tip to wing-tip measurement, to the chord is referred to as the *Aspect Ratio.* A rectangular wing with a span of 30 ft. and a chord of 5 ft. has an aspect ratio of

30/5 = 6. This is approximately the aspect ratio of a Lancaster bomber. Gliders may have aspect ratios as high as 20. Aircraft of two different aspect ratios are illustrated in fig. 11.

If the wing is not rectangular, and, of course, wings seldom are, an equivalent ratio may be contrived by the mathematical process of integration or arrived at in the following way:

$$\text{Aspect Ratio} = \frac{\text{Span}}{\text{Chord}} = \frac{\text{Span}}{\text{Chord}} \times \frac{\text{Span}}{\text{Span}} = \frac{(\text{Span})^2}{\text{Area}}.$$

This alternative formula is independent of the changing chord, and is really equivalent to using an average chord length in the original definition.

Wings that are tapered and wings with rounded or raked tips (see fig. 12) give slightly more lift and less drag than wings of rectangular shape. The best shape of all is the elliptical shape used on the Republic, the Thunderbolt and the Spitfire.

(*b*) *In Cross-section.* A very large number of different shapes in cross-section have been tested in the laboratory. The effect of the various changes in shape is somewhat complicated, but the more important results are these: The wing with a highly cambered upper surface and thick cross-section will give greater lift and in addition will provide room for stronger spars. It will, unfortunately, give more drag. Such wings are useful where the maximum lifting power is required, as in the case of bombers and transport planes.

The wing with only slightly cambered upper surface and thinner cross-section will not give so much lift, but will give less drag. Such wings are used for high-speed fighters.

Movement of the centre of pressure, which is always a nuisance to the designer, may be limited in extent by using wings of almost symmetrical cross-section or wings in which the trailing edge curves slightly upwards (reflex trailing edge). Although such wings have a very small centre of pressure travel, this is only achieved at the expense of lift.

Some of these shapes are illustrated in fig. 13.

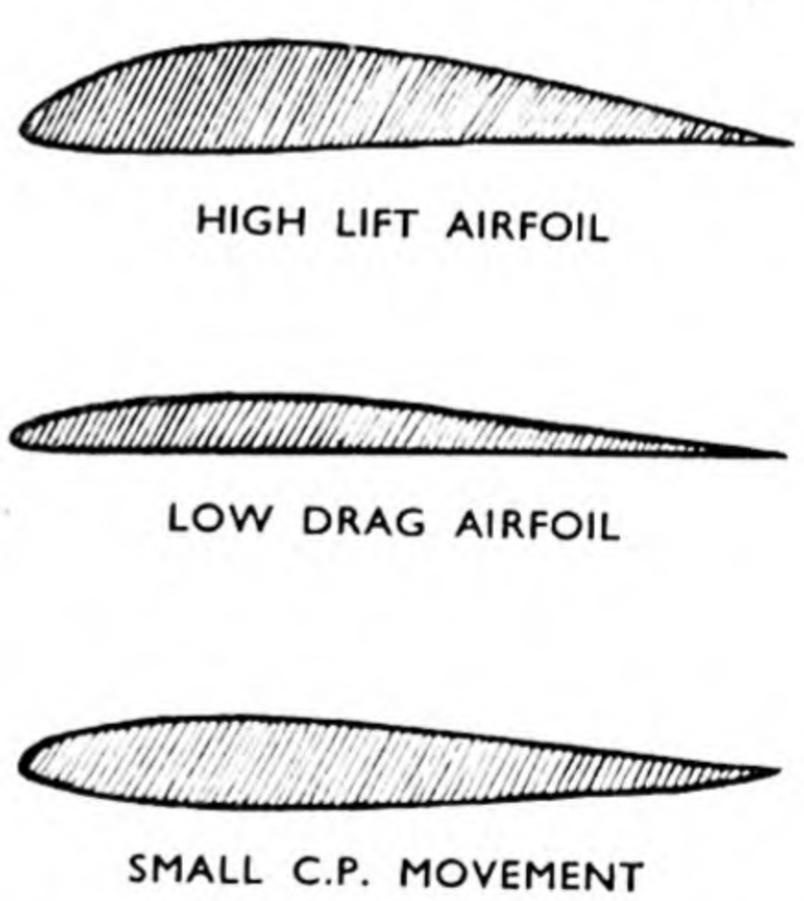


Fig. 13.—Variation in cross-section

2. *AREA.*

All other things being equal, the lift and the drag of a wing both increase in direct proportion to its area. This means that if the area is doubled, the lift and drag are doubled also. Bigger aircraft need bigger wings.

3. *DENSITY OF THE AIR.*

If nothing else varies, the lift and the drag are both directly proportional to the air density. In other words, the thinner the air, the less support it gives to the aircraft, but the less is the drag that tries to prevent its motion through the air. This is of interest in flying at great heights, where the air is less dense than near the ground.

4. *SPEED THROUGH THE AIR.*

It can be shown by experiment with an airfoil in front of a wind-tunnel (fig. 14) that the lift and the drag vary greatly with the speed of the airflow past the airfoil. The greater the speed of the air, the greater the lift and the drag, but here the law is not one of direct proportion, for the lift and the drag are *proportional to the square* of the airspeed. If the speed of the air is doubled, both lift and drag are multiplied by four; if trebled, they are multiplied by nine.

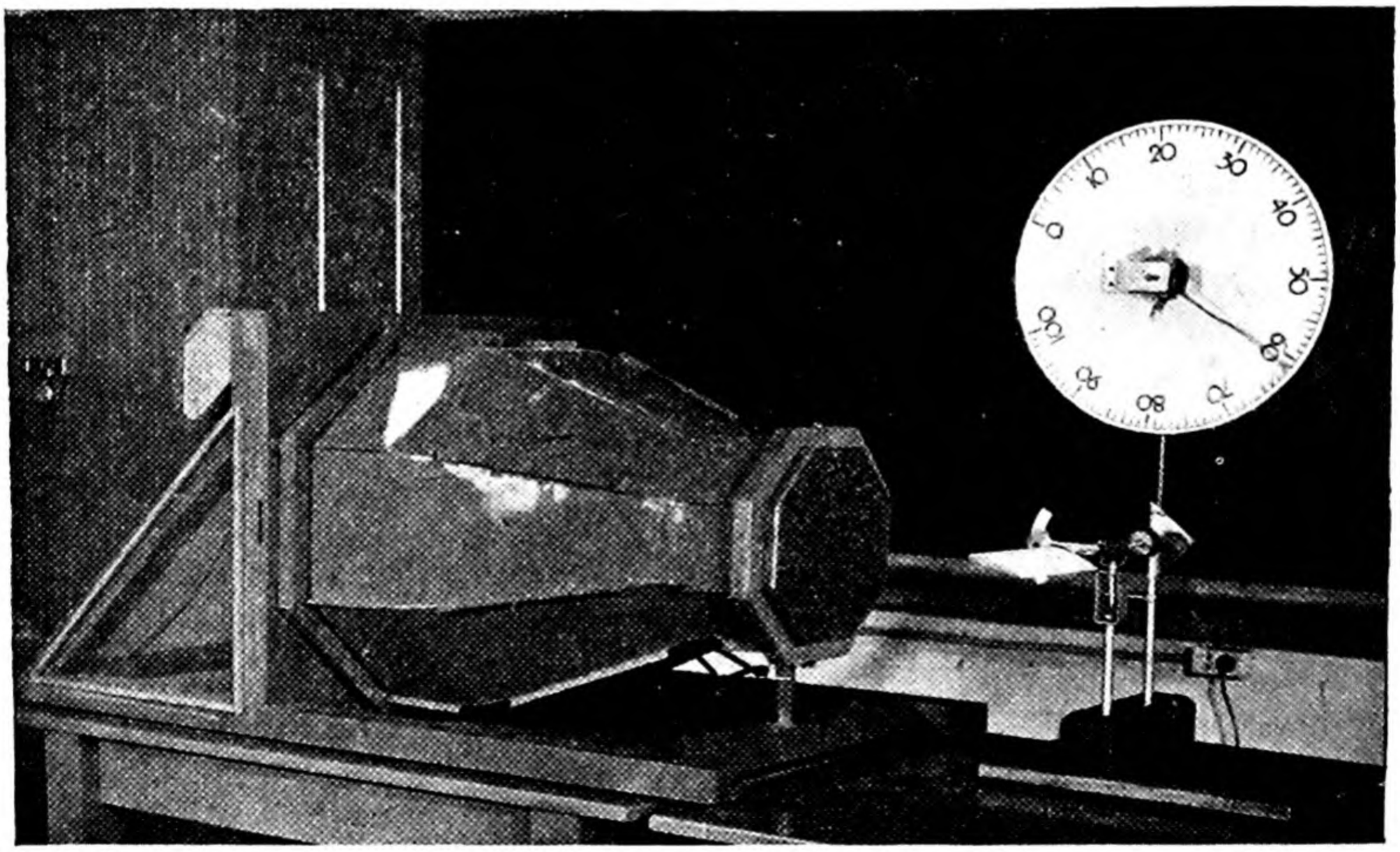


Fig. 14.—Measuring the lift from an airfoil in front of a wind-tunnel

5. *ANGLE OF ATTACK.*

The effects produced by alteration of the angle of attack are the most interesting and important of all. Provided that only the angle of attack is altered, and that the airfoil shape and area, the airspeed and density are kept the same, the results shown in fig. 15 are obtained by experiment.

Lift increases rapidly and smoothly from zero at about −5° angle of attack. It does not increase indefinitely, however, and at an angle of attack near 15° the rate of increase begins to fall off, a maximum is

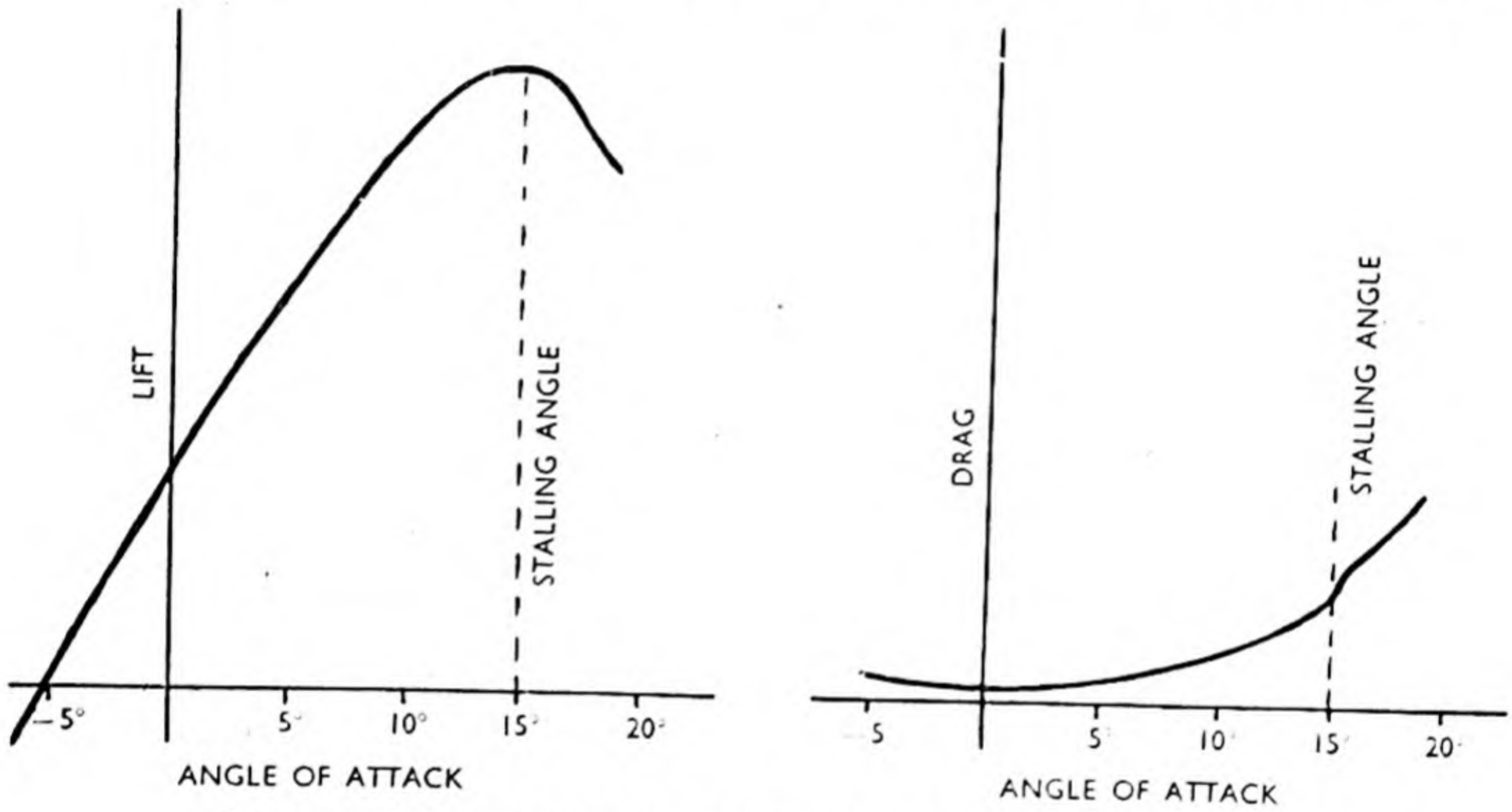


Fig. 15.—Graphs showing how lift and drag vary with angle of attack

reached at about 15°, and thereafter the lift drops sharply with further increase in angle of attack. *The angle of attack at which lift is a maximum is called Stalling Angle. Drag* on the airfoil at small angles of attack is very much less than the lift. It shows a minimum value at about 0° angle of attack, increases slowly at first, but more rapidly at and after stalling angle.

The five factors on which lift and drag depend may be summarized thus:

1. *Shape*, (*a*) in plan, (*b*) in cross-section;
2. *Area*, directly proportional;
3. *Density*, directly proportional;
4. *Speed* through the air (proportional to the square);
5. *Angle of attack*;

and may be remembered by " *S* ome *A* ircraft *D* o *S* plendid *A* erobatics ".

Stalling of a Wing.

Experiments with smoke in wind-tunnels show conclusively that the drop in lift and rapid rise in drag that occur as the angle of attack passes the stalling angle are due to a change in the character of the airflow over the upper surface of the wing. The smooth airflow breaks away from the top of the wing, leaving a turbulent wake between the wing and the undisturbed airflow above. At first only the part near the trailing edge is affected, but then, usually quite suddenly, the whole of the airflow breaks away right up to the leading edge (fig. 16). The wing is stalled.

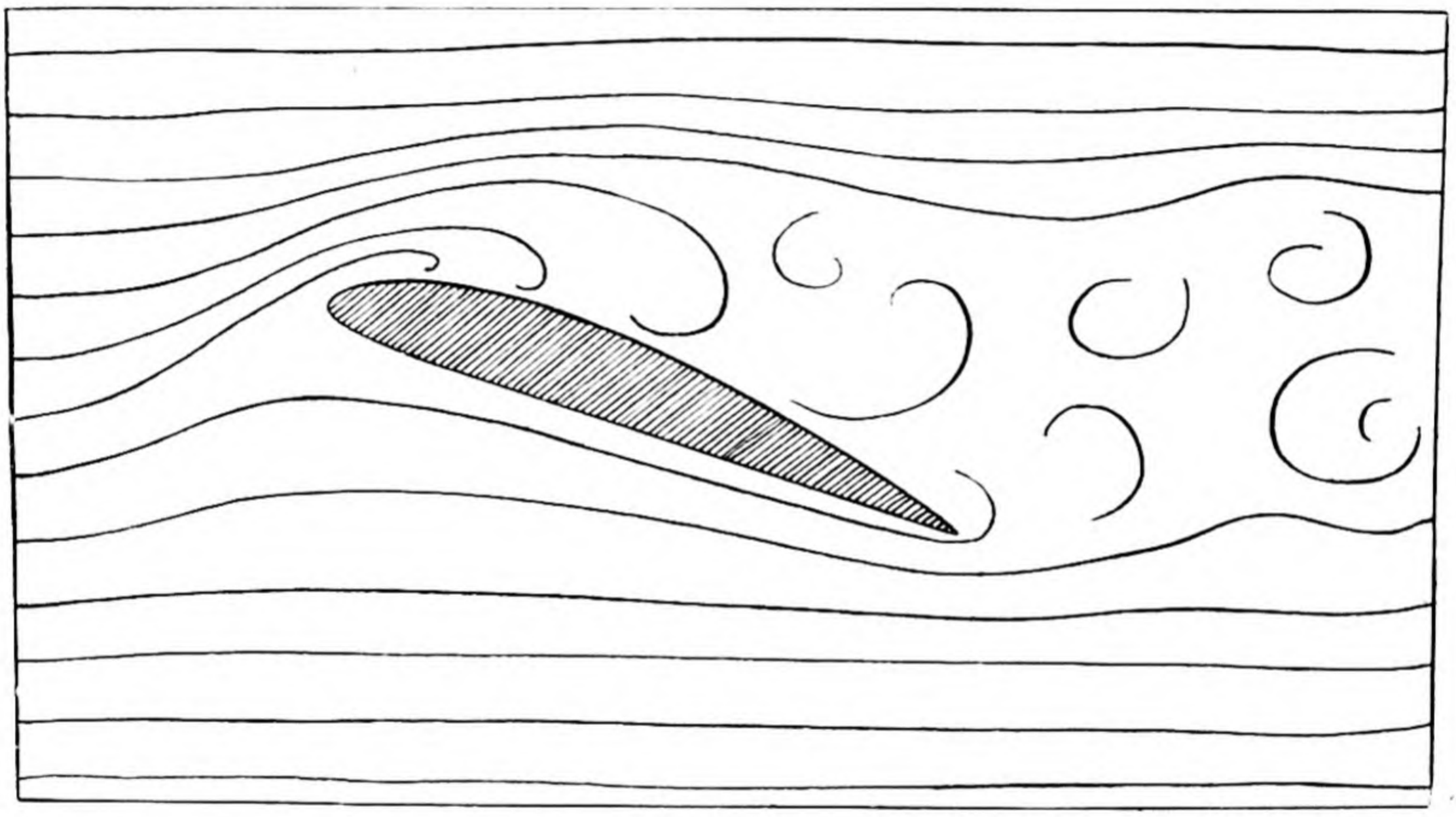


Fig. 16.—Airflow about a stalled wing

Since the airflow over the wing is no longer smooth and the Venturi principle is no longer at work, there is but little reduction of pressure there, and loss of lift results. The turbulent nature of the air that is left behind a stalled wing tells us that the wing is moving forward against increased drag forces. The energy used in working against this increased drag has reappeared as energy of motion in the whirlpools or eddies left behind.

A sudden stall is a characteristic of certain airfoil sections; with others the change is spread over several degrees of angle of attack. A flat plate stalls sharply at an angle of attack much smaller than is common with well-shaped wing sections, in which the air is deflected less suddenly near the leading edge. This accounts, in part, for the

smaller reaction obtainable from a flat plate. If some means can be found by which the stalling angle of a wing can be postponed, then further increase of lift may be obtained by using angles of attack beyond the normal. Mention is made later of a device which can be fitted to the wing for this purpose. The device is called a " leading-edge slot " (p. 56).

Connexion between Stalling Angle of the Wing and Stalling Speed of the Aircraft.

Generally speaking, the first three factors considered are not the concern of the pilot but of the designer, who tries to find the best shape and area to give the most lift and the least drag for the conditions under which the aircraft, in the main, will operate. The last two factors, speed through the air and angle of attack, are under the direct control of the pilot, who, by flying the aircraft in the best attitude and at the best speed for the particular conditions, gets the best out of the wings with which the aircraft is provided.

The connexion between airspeed and angle of attack is very important, and every endeavour should be made to understand it thoroughly.

Imagine an aircraft flying straight and level at, say, 150 m.p.h. If the pilot, wishing to increase his airspeed, opens the throttle farther, then the increase in speed will increase the lift from the wings. This would cause the aircraft to gain altitude. The lift must somehow be maintained at its former value, at which value it just counterbalanced the weight of the aircraft. The pilot is not only able to vary the speed of his aeroplane, but also its attitude, and in this way alter the angle of attack of the wings, and so the pilot lowers the angle of attack of the wings by flying his aircraft with the nose a little lower. Thus, by using a smaller angle of attack with the higher speed, the same lift is retained, and the aircraft continues to fly at a constant height.

Suppose the opposite case is considered. The pilot closes the throttle somewhat and decreases the airspeed. The decrease in lift that would result from this alteration alone is prevented by the pilot's flying the aircraft with the nose a little higher, i.e. using a larger angle of attack. Perhaps the original angle of attack was 4° when the airspeed was 150 m.p.h., whilst now, at the airspeed of 120 m.p.h., it has been found necessary to increase the angle of attack to 6°. A further decrease of speed to 100 m.p.h. might need an angle of attack of 10°. *It can be seen that for level flight each angle of attack is asso-*

ciated with a particular airspeed. In fast flight the nose is slightly down, whilst at low speed the nose is high.

The airspeed cannot be decreased indefinitely in this way, for, when the stalling angle of the wing is reached, any further attempt to restore the lift by increased angle of attack will only result in a decrease in lift. Furthermore, drag increases rapidly with increased angle of attack at this stage, tending to slow down the aircraft still more, and so aggravate the situation.

There is, therefore, a minimum speed at which the aircraft can maintain level flight, and *when the aircraft is flying at this minimum speed, the wings are at stalling angle of attack.* The minimum speed that the aircraft can maintain in level flight is called the *stalling speed of the aircraft*, or more strictly, stalling speed in straight and level flight.

Note that the phrase " stalling speed of a wing " has no meaning in this connexion. The stalling angle of a wing is very much the same at all speeds.

Movement of the Centre of Pressure with Alteration of the Angle of Attack.

As the angle of attack is increased from the value where lift is zero, the centre of pressure moves forward towards the leading edge. At 0° angle of attack it is usually about half-way back. As the angle of attack increases to about 12° the centre of pressure moves forward until it is about one-third of the way back.

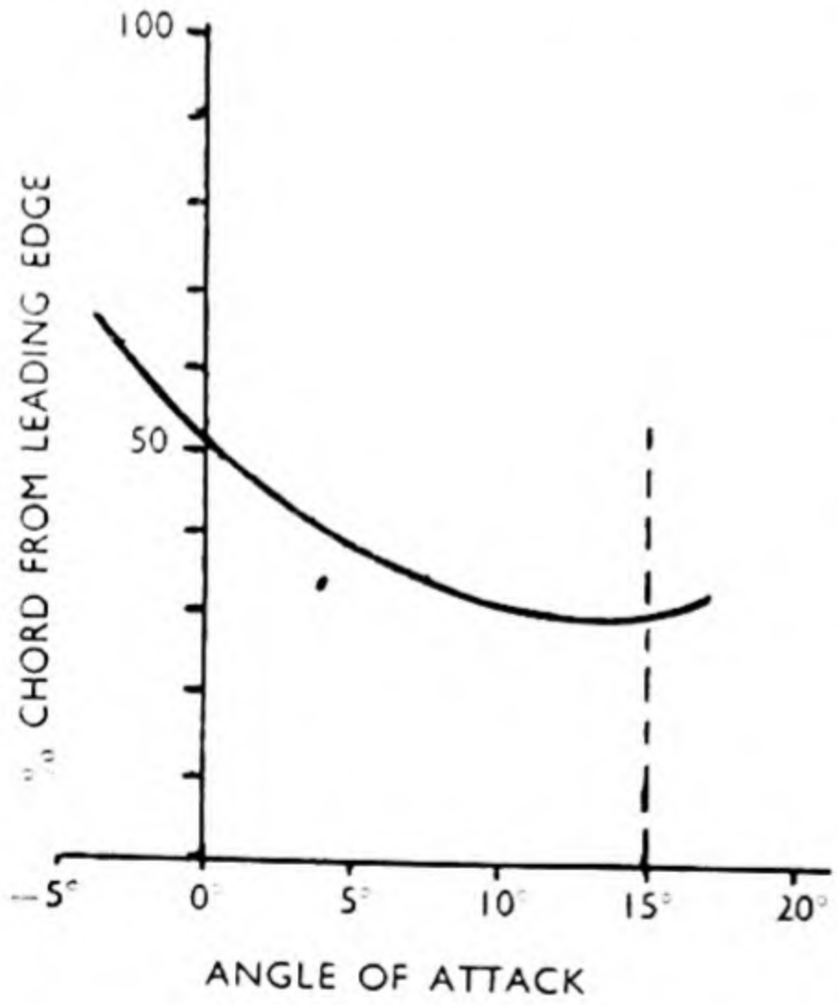


Fig. 17.—Graph showing how the position of the centre of pressure alters with changing angle of attack.

Near the stalling angle the centre of pressure, having reached its most forward position, begins to move back slightly towards the trailing edge, and this movement continues through the stalling angle. The forward movement during the normal angles of attack is mainly attributable to the building up of reduced pressure on the upper surfaces near the leading edge, whereas the backward movement as the angle of attack reaches the stalling angle may be explained by the sudden breakdown of the area of reduced pressure when the wing stalls. A graph of centre of pressure position against angle of attack is given in fig. 17.

Character of Stall.

At one time in the history of flight stalling was a much-feared mysterious bogy, but now that we understand it, it has taken its place as an everyday manœuvre that is part of the pilot's training.

Different aircraft show differences in the way in which they stall. Some stall reluctantly, gently subsiding after a period of partial stall during which the air can be felt burbling over the trailing edge of the wings and buffeting the tail. Others stall suddenly, especially if the wing flaps are down. In most cases one wing will stall first, and always the nose of the aircraft will drop.

Stalling an aircraft near the ground has probably been responsible for more accidents in flying than any other cause. Owing to the low height, the machine has no time to recover. It is perfectly safe for a skilled pilot to stall an aeroplane at *such an altitude* that the machine has sufficient height to regain normal flying speed and reduce the angle of attack of the wings to below stalling angle, but this cannot be done when the aircraft is low, because of the lack of room.

BIPLANES AND MONOPLANES

Any talk on the subject of wings would be incomplete without a mention of the biplane, even though it has been superseded by the monoplane for almost all Service types.

In the early days of flight, when engines of small horse-power made any but the lowest speeds impossible, it was necessary to obtain sufficient lift by a resort to very large wing area. By arranging the wing area as 2, 3 or even 4 wings, one above the other, a form of construction was achieved that was both light and convenient.

It has always been realized that as far as the principles of flight are concerned, such an arrangement was less efficient, because the placing of one wing above the other causes interference between the increased pressure on the under side of one wing and the decreased pressure on the upper surface of the wing below it. This interference results in some loss of lift to both wings, the bottom wing suffering more because the upper surface of any wing is the more important.

If the leading edge of one wing is placed ahead of the leading edge of the other wing in a biplane, the wings are said to be *staggered*. Usually, the upper wing is the one which is farther forward; this is called forward stagger. Stagger decreases somewhat the interference between the wings, but possibly the main reason for its widespread

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use lies in the fact that forward stagger greatly improves the field of view of the pilot.

If the wings are placed farther apart, one above the other (increasing the " gap "), the interference is reduced, but if the gap becomes too great, the increase in weight due to the lengthened struts and wires more than counterbalances any extra lift.

The second aerodynamic disadvantage of the biplane lies in the considerable increase in drag caused by the interplane struts and bracing wires.

The biplane, however, is not without its advantages. It is very manœuvrable, it takes up little space, and it gives a light and easy form of construction.

With improvement in both power and power-weight ratio of aero-engines, higher speeds, and therefore smaller wing areas, became possible. At the same time improved methods and materials of construction were made available to the designer. These together brought about a new type of aeroplane: a monoplane without external bracing of any kind. Thus, higher speeds have helped to produce a wing with less drag, and the wing itself has repaid this debt by helping to give even higher speeds.

Early aircraft with large wing areas had very low minimum speeds, and were therefore easy to land. More modern aeroplanes land at higher speeds because, relative to their weight, their wing areas are smaller.

Factors upon which Stalling Speed depends in Straight and Level Flight.

1. *Weight.* In order that the aircraft may maintain height, the lift from the wings must be sufficient to counterbalance the weight of the aircraft. If we can imagine the weight of an aircraft being increased without any alteration other than this, then it follows that an increased lift will be required to maintain level flight. If the aircraft is travelling with the wings at stalling angle and therefore at stalling speed, it cannot gain this extra lift by alteration of the angle of attack. The only other factor that can be varied (apart from the flaps, which we must leave to a later stage) is the speed, and so the speed must be increased. The stalling speed of an aircraft is therefore increased by increasing the weight. If an extra load is taken aboard in freight or men, the stalling speed of the aircraft will be greater than it was before.

2. *Wing Shape.* The use of a wing of high camber or high aspect

ratio will enable a higher lift to be obtained from a wing of given area. This makes a lower minimum speed possible.

3. *Wing Area.* A reduction of wing area will of course decrease the lift obtainable at any given speed, and the lowest speed possible with small wings will always be higher than that with large wings.

4. *Density of the Air.* Other factors being equal, lift is less at high altitudes where the air density is small. In order to maintain sufficient lift to support the aircraft, higher speeds will have to be used. Stalling speed, therefore, increases with an increase in the altitude at which the aircraft flies. A word of warning is necessary here. The instrument in the aircraft that tells the pilot his airspeed, the Airspeed Indicator, is also affected by change of air density, and reads too low in air less dense than that for which it was calibrated. The pilot and navigator are well aware of this, and are accustomed to correcting the indicated airspeed for this error. It so happens, however, that the airspeed indicator error increases at the same rate as stalling speed, for both changes depend in the same way upon air density. In consequence, the stalling speed read directly from the airspeed indicator is the same at all altitudes—a very useful thing for the pilot, who has therefore only one stalling speed to remember.

Wing Loading.

About half the drag of an aircraft is due to the wings. In an endeavour to reduce the drag, designers of aircraft have gradually reduced the size of the wings relative to the weight they must lift. Unfortunately, this is not without its disadvantages, for it has been necessary to compensate for the smaller wing area by using higher speed. Stalling speeds, and therefore landing and take-off speeds, have become higher and higher.

Wing loading may be defined as the ratio of wing area to total aircraft weight, and is usually given in lb. per square foot. Thus, for an aircraft weighing 6000 lb. and having a total wing area of 200 sq. ft., we have:

$$\text{Wing loading} = \frac{\text{Total weight in lb.}}{\text{Wing area in sq. ft.}}$$

$$= \frac{6000}{200} \text{ lb. per sq. ft.}$$

$$= 30 \text{ lb. per sq. ft.}$$

Every square foot of wing, therefore, supports in level flight an average of 30 lb.

It is clear that an aircraft with a high wing loading has small wings for its weight, and must have a high stalling speed. If the wing loading is low, then the aircraft will stall, land, and take-off at low speed.

As a pilot under training progresses from training types of aircraft with wing loadings of about 8 lb. per square foot to advanced trainers with wing loadings of 10 or 12, and finally to operational types with wing loadings of 30 or more lb. per square foot, he will be dealing with faster and faster landing speeds. A Tiger Moth touches down at about 45 m.p.h. airspeed, a Hurricane between 80 and 90 m.p.h., and the Mosquito between 110 and 120 m.p.h. There is no simple mathematical connexion between stalling speed and wing loading, but it is possible to make a shrewd guess at the one if the other is known.

QUESTIONS

1. Make a clear diagram of a wing section at an angle of attack of about 5°, showing the airflow above and below the wing. Mark on it:

(*a*) The chord.
(*b*) The angle of attack.
(*c*) The regions of upwash and downwash.
(*d*) The regions where the airspeed is faster and where it is slower than normal.
(*e*) The regions where the air pressure is higher and where it is lower than normal.

2. An airfoil is placed in front of a wind-tunnel and the lift (L) and drag (D) are measured. What effect would the following changes have on (L) and (D), other factors being unaltered?

(*a*) Doubling the area.
(*b*) Doubling the speed.
(*c*) Replacing the airfoil by a flat plate at the same angle of attack (assuming the plate does not stall).
(*d*) Increasing the angle of attack from 0° to 5°.
(*e*) Increasing the angle of attack from 12° to 25°.

3. (*a*) Draw an airfoil section to represent a wing moving through the air at an angle of attack of about 5°, and mark and label on the diagram the following:

1. The chord.
2. The centre of pressure.
3. The direction of motion and the relative wind.
4. The lift and drag forces.
5. The angle of attack.

(*b*) What alteration do you expect as the angle of attack is raised to 22° in:

1. The value of the lift force?
2. The character of the airflow about the wing?

4. A Sunderland flying-boat picks up the crew of a bomber, nine men, who have been forced into the sea. What difference, if any, will this make to the aircraft's:

1. Stalling speed in level flight?
2. Wing loading in level flight?
3. Landing speed?
4. Total drag at a given cruising speed?
5. Angle of attack of the wings at a given speed?

5. (*a*) Draw a diagram of a wing section to show the pressure distribution about it in flight at an angle of attack less than the stalling angle. Label the regions of low and of high pressure.

(*b*) Draw a similar diagram to show the pressure distribution when the wing is stalled.

(*c*) What changes in the character of the airflow have taken place to account for the difference between the two diagrams?

·6. An airfoil is suspended in front of a wind-tunnel where the velocity (*V*), the density (*D*), the lift (*L*) and the drag (*D*) can be measured. Other factors remaining unaltered in each case, what will be the effect of:

(*a*) Doubling the area of the wing?
(*b*) Replacing it with one of greater upper camber?
(*c*) Increasing the aspect ratio?
(*d*) Halving the velocity of the air?
(*e*) Halving the density of the air?
(*f*) Increasing the angle of attack slowly from 0° to 25°?

7. (*a*) Owing to engine trouble the speed of an aircraft starts to drop. In order to maintain height, the pilot increases the angle of attack of the wings. If he continues to do this, describe and explain what will eventually happen.

(*b*) What happens to the stalling speed of an aircraft in level straight flight when altitude is increased:

1. In terms of true airspeed?
2. In terms of the airspeed indicator?

8. (*a*) Illustrate the airflow about a wing at an angle of attack below stalling angle by means of an airfoil section with the streamlines about it. Mark on the diagram the direction of motion of the wing through the air.

(*b*) Use this diagram to explain briefly the way in which the wing produces lift.

9. (*a*) Draw two diagrams of a wing section to represent a wing moving through the air, one at an angle of attack about two degrees below the stalling angle and the other at an angle of attack beyond stalling angle. Mark on your diagrams the position of the centre of pressure, and the lift and drag forces. Make the length of the lift and drag lines represent their size.

(*b*) Account for the alteration in the lift and drag forces.

10. (*a*) Define wing loading in level flight.

(*b*) Why is there a tendency in aircraft design towards higher wing loadings?

(*c*) What disadvantages accompany these higher wing loadings?

11. (*a*) What is the connexion between the stalling angle of the wing and the stalling speed of the aircraft?

(*b*) The stalling speed of a particular aircraft is not always the same. What are the factors that may cause it to vary?

12. A model aircraft has rectangular wings measuring 3 ft. from wing-tip to wing-tip, and with a 4-in. chord. It weighs $\frac{1}{3}$ lb. Calculate:

(*a*) The aspect ratio.
(*b*) The normal wing loading.

CHAPTER II

Drag, the Enemy of Flight

DEFINITION OF DRAG. FORM DRAG. SKIN FRICTION. LAWS OF AIR RESISTANCE: ALTITUDE, FRONTAL AREA, AIRSPEED, DENSITY. ANALYSIS OF AIRCRAFT DRAG: PARASITE DRAG, WING DRAG, COOLING DRAG.

Definition of Drag.

Drag is the resistance to motion offered to any body moving relative to a fluid. A teaspoon used to stir tea, a stick pulled through water, a swimmer breasting a river, a battleship thrashing its way through the sea, all experience to a lesser or greater degree the same force—a force always acting backwards along their line of motion trying to bring them to a standstill.

Although it is easier to move through air than through water, because of its smaller density, appreciable drag may be caused even by this invisible fluid. Most of the energy expended by a cyclist is spent in working against the drag caused by his movement through the air. For an aircraft in level flight, drag is the only force opposing it. It is the enemy of flight, and the designer of aircraft is always searching for ways of reducing it. A reduction in the drag will enable the maximum speed to be increased if the same engine is used, or, with the same top speed, the engine power may be reduced, with a saving in engine weight and fuel consumption, and an increase in range.

Form Drag.

A large part of the drag resisting the aircraft's motion is due to the disturbance of the air by the body moving through it, and the extent of the resistance is reflected in the amount of turbulence that is left behind. If the wake is full of eddies, then the energy used to create that motion has come from the work done against the drag forces. For instance, a plate with its flat side facing the airflow produces a large and turbulent wake, and offers considerable resistance to motion, but an object of the shape known as streamlined offers little resistance because there is little or no eddy behind it.

Drag of this sort is greatly influenced by the shape of the body. The following diagrams (fig. 18) show the appearance of the streamlines past a flat plate, a sphere, a cone with a hemispherical nose, and

a body of streamline shape like a raindrop. It is at once apparent from the amount of turbulence behind the flat plate, that this is the shape that requires most effort to push it forward. If the drag of the

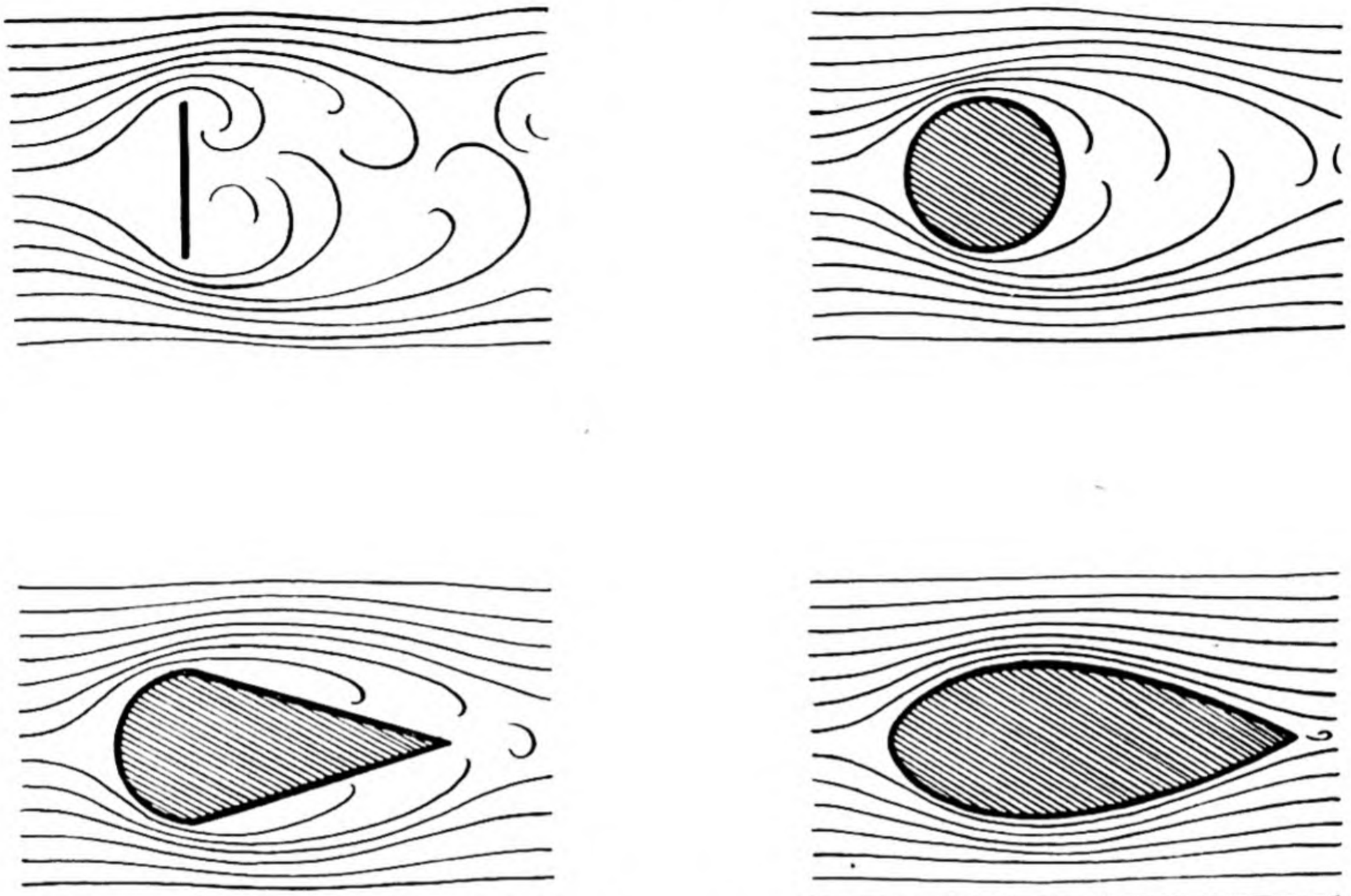


Fig. 18.—Showing how the shape influences the turbulence created in the airstream

flat plate is called 100 per cent, then the drag of the sphere may be put down as approximately 50 per cent, that of the third shape as about 30 per cent, whilst the drag force acting on the streamline

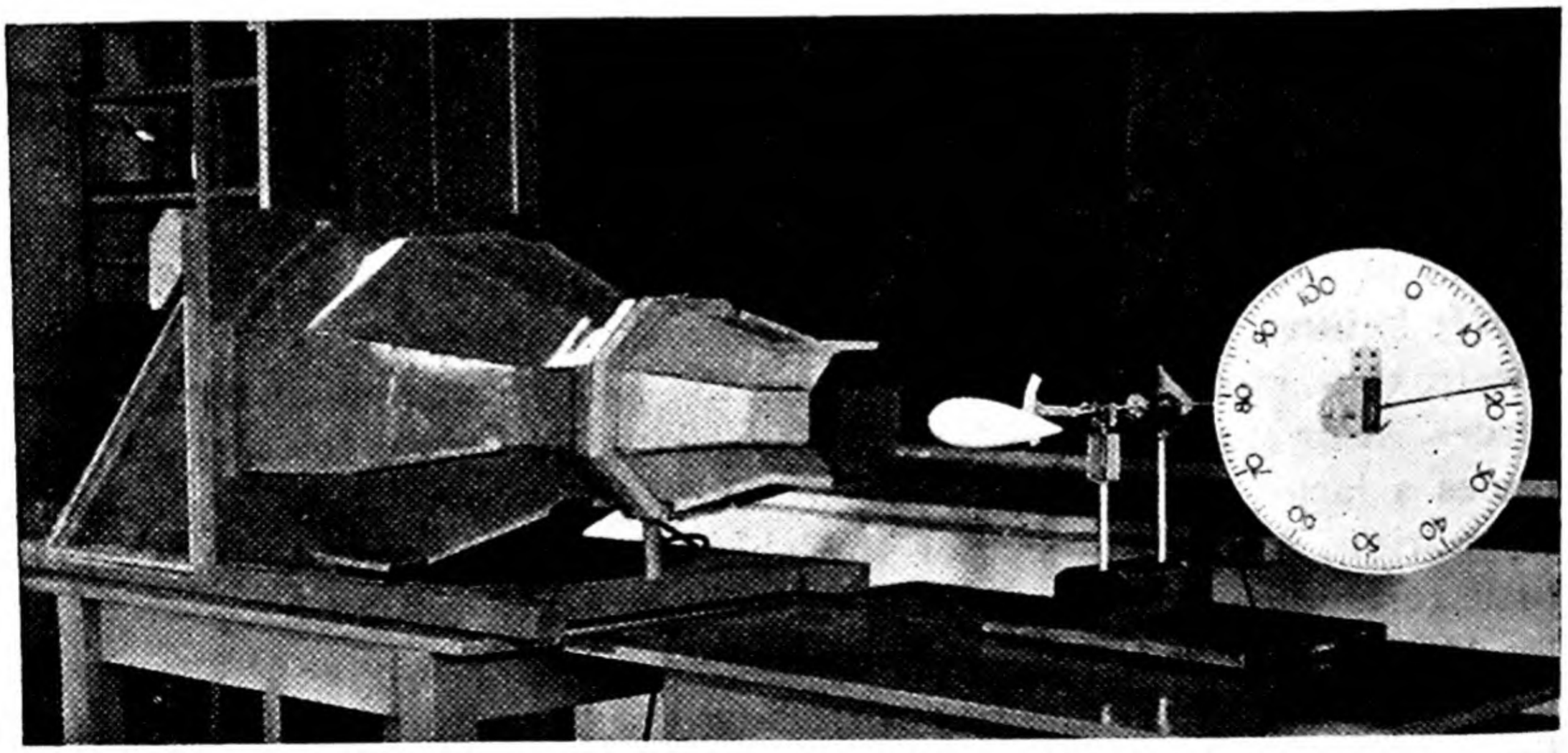


Fig. 19.—Measuring the drag of a streamlined shape in front of a wind-tunnel

shape may be as low as 5 per cent. This last figure shows that a remarkable reduction of drag can be effected by enclosing the flat plate in a streamline cover. Such a cover is called a *fairing*.

Skin Friction.

Bodies in an airflow experience a certain amount of drag in addition to that which arises from turbulence in the airstream. This is caused by a very thin layer of air next to the body which sticks to the surface and is partly carried along with it. This frictional force may be of relatively little importance in a badly streamlined shape, but notice must be taken of it when *streamlining is good and speeds are high*.

It can be observed that the dust on the wings of aircraft lies undisturbed after a flight. This means that the air in contact with the wing has been carried along at the same speed as the wing itself. The layer next to this one is dragged along too, but not quite so fast, and, in its turn, the next layer is effected in the same way, until air is reached where the effect of this viscous drag is no longer felt. All this takes place within a very thin surface layer, called the *boundary layer*, about $\frac{1}{30}$ of an inch in thickness, and the unaffected air beyond is called free air. The flow in this layer is termed *laminar*, which means simply "in layers".

There is, apparently, another kind of boundary layer, in which the flow is not laminar but turbulent. This layer may be $\frac{1}{4}$ of an inch thick or more, and is full of minute vortices caused by dragging the surface past the air in somewhat the same way as breadcrumbs will form into cylindrical pellets on a table if one's hand is rubbed over them. Beneath the turbulence there still exists a very thin laminar layer. This type of skin friction causes much more drag than the laminar flow, just as, on a very much larger scale, turbulence behind a wing indicates a greater drag than smooth flow.

Now on the surface of a wing or streamlined shape both kinds of layer may exist, the laminar flow near the leading edge or nose, and the turbulent flow over the rest of the surface. The change from one to the other occurs sharply, and may be precipitated by minute irregularities or roughness on the surface. The total drag experienced from skin friction depends to a large extent upon how far back the change takes place. Careful choice of shape, and the avoidance of lap joints, protruding rivet heads, and roughness of any kind all help to postpone the change to the turbulent layer. Methods have been suggested, and tried, whereby the laminar flow may be restored by sucking away the turbulent layer through slots in the surface, or,

alternatively, by blowing it away with a jet of air ejected at high speed backwards and close to the surface through holes. At present these methods of reducing skin friction remain in the experimental stage.

Laws of Air Resistance. (See fig. 20.)

What has been written so far may be summarized by stating that the total resistance to motion experienced by a body moving through air depends on the shape and smoothness of surface. This, however, is not the whole of the story.

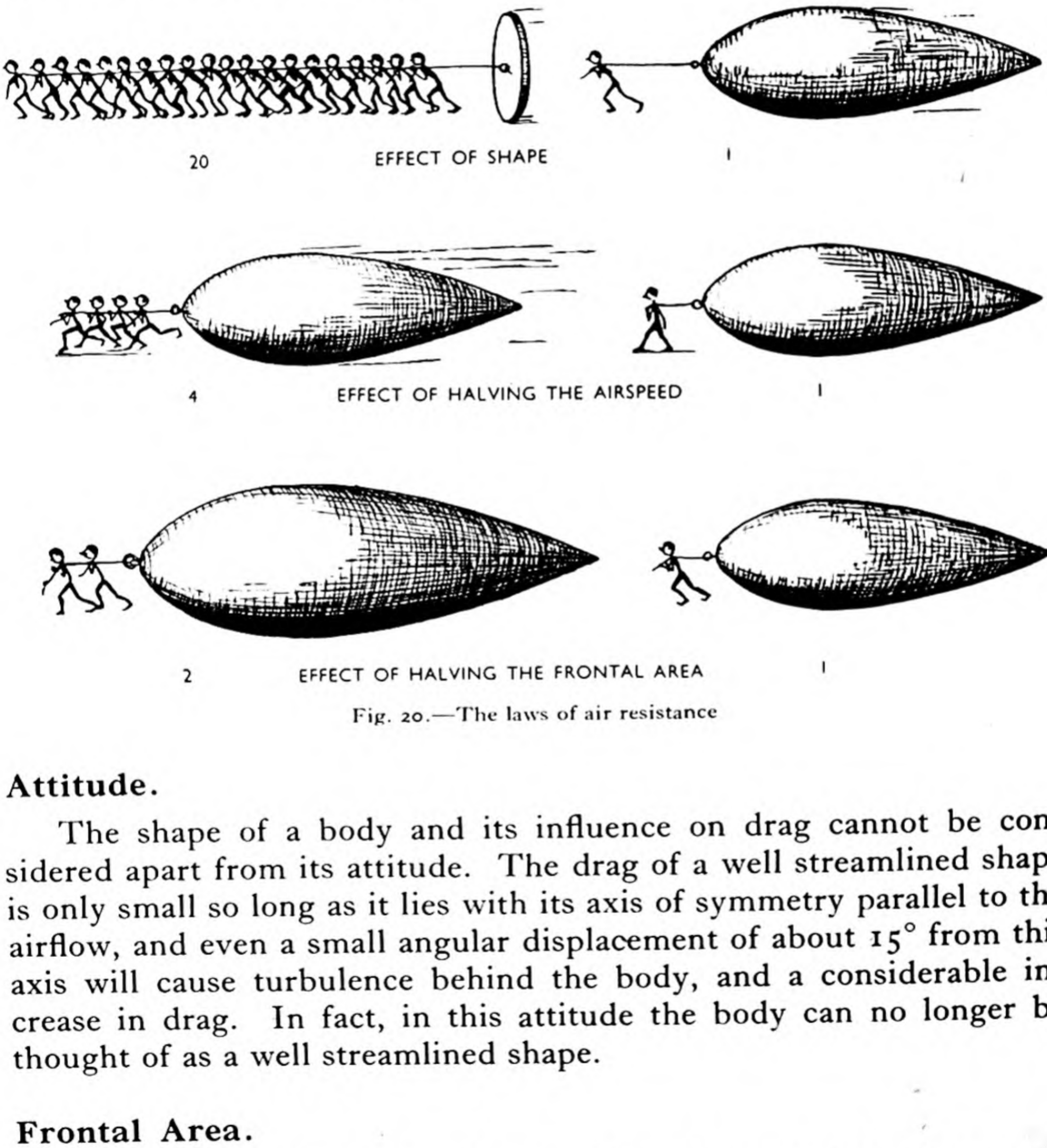


Fig. 20.—The laws of air resistance

Attitude.

The shape of a body and its influence on drag cannot be considered apart from its attitude. The drag of a well streamlined shape is only small so long as it lies with its axis of symmetry parallel to the airflow, and even a small angular displacement of about 15° from this axis will cause turbulence behind the body, and a considerable increase in drag. In fact, in this attitude the body can no longer be thought of as a well streamlined shape.

Frontal Area.

It is obvious that large objects will cause more drag than small ones of similar shape, both because of the greater disturbance they

must create and also on account of the larger surface area. In discussing the influence of shape on form drag, four bodies were chosen each having the same frontal area. If one particular shape is taken, and its *frontal area* doubled, it is found that the drag is doubled also. In fact, drag is directly proportional to frontal area.

Airspeed.

The influence of speed on drag is even more pronounced, for if airspeed is doubled, the drag increases fourfold. Drag is proportional to the square of the airspeed.

Density.

Although this is not easy to verify by experiment, it is known that drag decreases as air density becomes smaller, and that drag is directly proportional to air density.

No doubt the similarity of these experimental laws to those already enumerated for lift and drag of an airfoil will be apparent to the reader. This is because the wing is merely a particular kind of shape to which, of course, these general rules apply. An airfoil is a shape specially designed to give a large reaction as nearly at right angles to the airflow as possible; with a symmetrical shape all the reaction is in a direction opposite to that in which the body is moving.

The effect on drag of the attitude of the wing was considered in terms of angle of attack. The attitude of the other parts of the aircraft is not of such vital importance, but even a fuselage may give *some* lift when not facing directly into the airflow, and drag will certainly be increased. It is a definite help to a quick take-off to get the tail up as soon as possible, so that the aircraft shall not be held back by unnecessary drag.

As for area, it is purely a matter of convenience as to whether plan area or frontal area is used when stating the connexion between drag and the size of the body. Both areas vary in the same way, and, if one is changed, the other changes in the same proportion. It is customary to use plan area when working with airfoils, and frontal area for other bodies.

The designer must predict as nearly as possible the total drag of the aircraft before it is completed, and for him the laws of drag are familiar as mathematical formulæ.

ANALYSIS OF AIRCRAFT DRAG

Parasite Drag.

About half of the drag of the aircraft is due to the fuselage and parts other than the wing, and about half is due to the wings themselves. The drag of the parts other than the wings is not giving any compensation in the way of lift, and is therefore called *Parasite Drag*. Drag considered under this heading is made up of *form drag* and *skin friction*, the two types of drag so far considered.

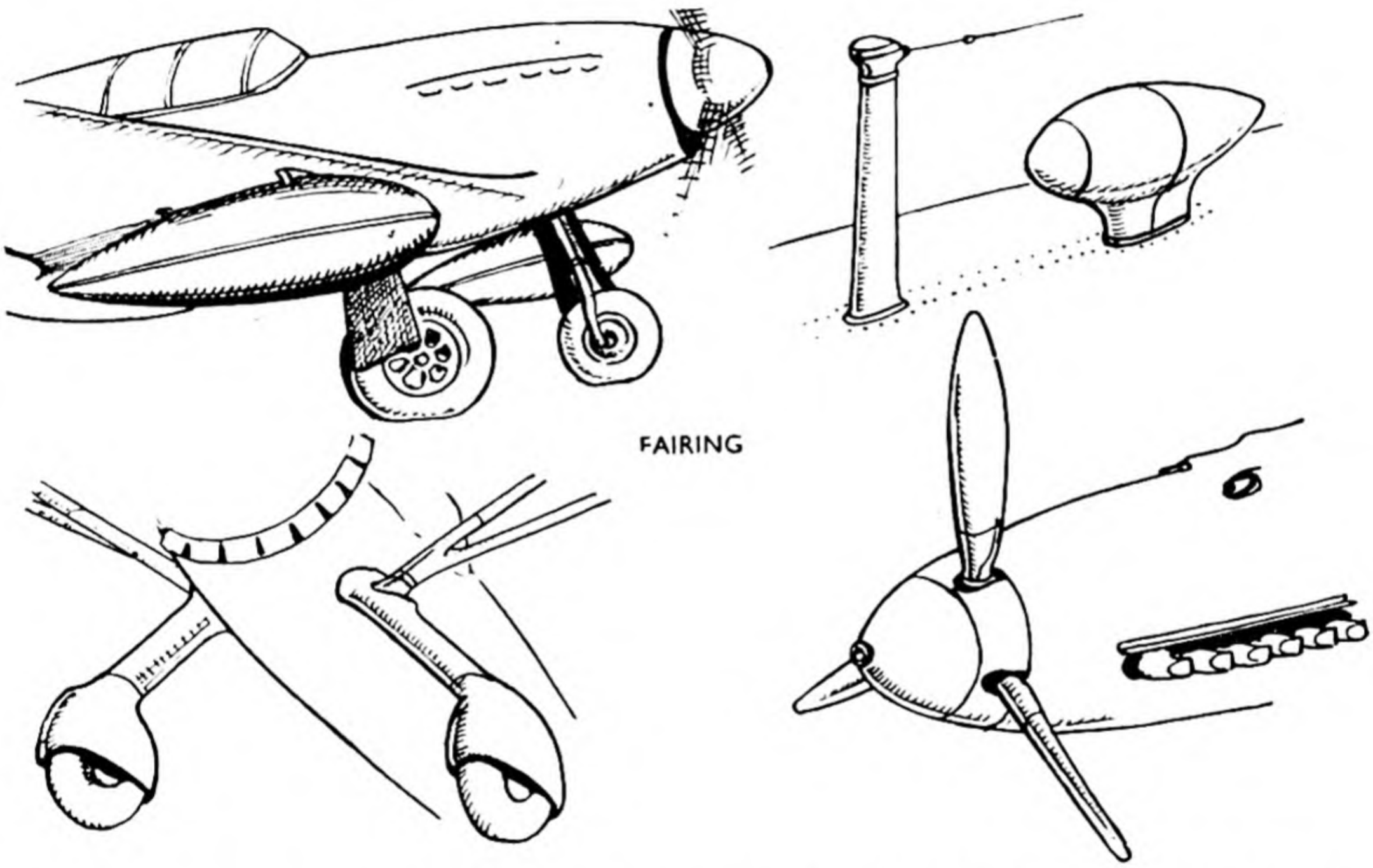


Fig. 21.—In the picture are: streamlined auxiliary petrol tanks; faired aerial mast, loop aerial, undercarriage and wing struts, wheel spats and propeller spinner

The *form drag* can be reduced by careful streamlining and by keeping the size of the fuselage, &c., to a minimum. It is interesting to see how this has been done (fig. 21) with such parts as the fuselage itself, the engine, the loop aerial (by enclosing it within a "fairing" of streamline shape), the wires and struts of the biplane, the wheels (by retracting them or by covering them with spats). It is as well to remember that the additional weight and complication of the retractable undercarriage, and the fact that when down it offers more resistance than the older type, which was streamlined, make the retractable undercarriage a not unmixed blessing.

A special word is necessary about the fairing of the air-cooled radial engine. An aircraft with an uncowled engine of this type would have a parasite drag often more than twice that of the fuselage without the engine. Research has led to the development of low-drag cowls that reduce the drag of the engine by more than half, by restricting the flow of air over the radiators to just that which is needed for cooling, and by compelling the air to flow round the nose in a manner that minimizes the eddies along the fuselage behind the engine. Two types of cowling (see fig. 22) are in use: the Townend ring and the N.A.C.A. cowling. The cowling developed by the National Advisory Committee for Aeronautics has a deeper chord than the Townend ring.

N.A.C.A. cowling — Townend ring

Fig. 22.—Two types of low-drag cowling

Wind shields, tail-wheels, outside aerial supports, all receive attention. Military aircraft, however, must often sacrifice aerodynamic efficiency to military expediency, and the necessity for gun turrets, to take one example, makes the best streamline shape impossible.

The more the form drag is reduced, the more notice must be taken of *skin friction*. With the old type of biplane, slow in speed and encumbered with struts and wires, it was largely a waste of time to smooth the surface, but with the cleaner design of modern fast fighter aircraft, a smooth surface is a very definite advantage.

Although it is possible to calculate fairly accurately the drag of each separate part of the aircraft, this does not necessarily mean that the total drag will be the sum of all the individual items. At the wing roots, for instance, where the wing joins the fuselage, eddies may exist at the trailing edge. A special fairing, called a *fillet*, is often fitted to high-speed aircraft in order to lead the air smoothly past this corner, and reduce this interference drag.

Wing Drag.

Wing drag is made up partly of form drag and skin friction (sometimes linked together under the name *profile drag*), but there is another source of drag peculiar to the wing, called *induced drag*.

Form drag of the wing is partly responsible for the shape of the drag curve when drag is plotted against angle of attack. Owing to the fact that the shape of the wing is designed to give lift, and not merely to give the best streamline shape, it is impossible to get rid of the eddies behind it completely, though they are very small at small angles of attack. The peculiarity of the wing is the way in which it stalls, so that at large angles of attack it leaves behind it a large number of eddies, giving a very considerable form drag in that attitude.

Skin friction of the wing is especially important on the upper surface where the air is travelling faster than the normal airspeed. Flush riveting and the elimination of lapped joints may effect considerable improvement in this respect.

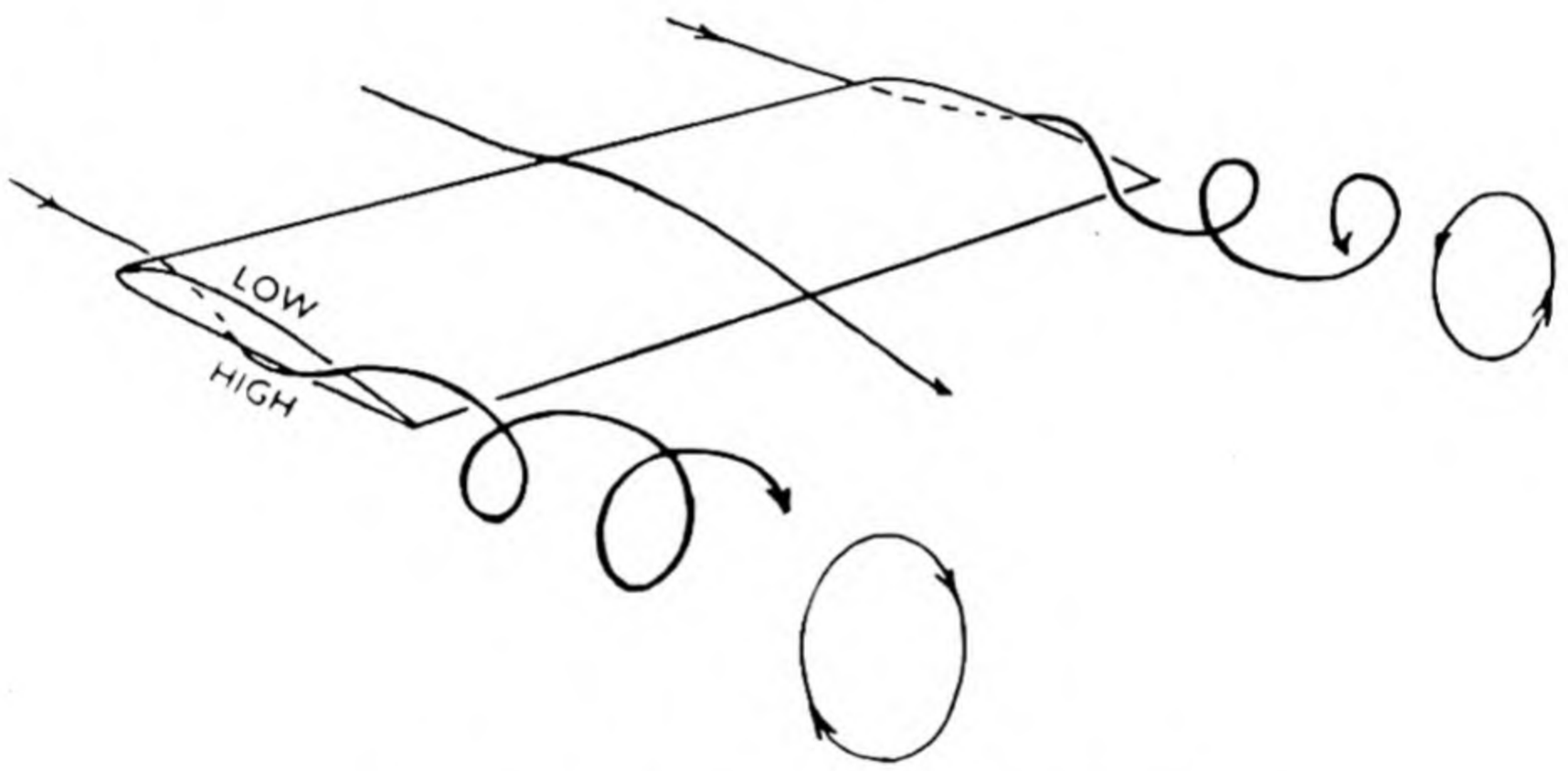


Fig. 23.—How wing-tip vortices are formed

Induced drag is the price that must be paid for lift, for it exists because the wing is lifting. The lower pressure on the upper surface of the wing causes the air to flow in a direction inclined inwards to the root, whilst underneath, the raised pressure causes the airflow to flow outwards to the wing-tip as well as backwards. As a result, when the two lots of air meet at the trailing edge, they twist round each other in the form of spiral vortices. It is a peculiarity of such vortices that they cannot exist like this, for it is a state of unstable equilibrium; they run into each other and form one big vortex at each wing-tip as shown in fig. 23. These are shed from the ends of the wings and left behind the aircraft as it moves through the air. They therefore represent lost energy, and by the reasoning that has been used before, this means extra drag.

If it were possible to have wings without ends, i.e. if the wings had an infinite aspect ratio and extended to an infinite distance, then there

would be no wing-tip vortices, and there would be no drag resulting from them.

Not only is drag increased by the state of affairs at the end of the wings, but there is some loss of lift. This is due to the spill at the wing-tips; in other words, when the air spills round the wing-tips from the lower to the upper surface it tends to neutralize the very pressure difference upon which the wing depends for its lift. It is found that, owing to this end effect, the lift begins to fall off from the theoretical value near the tips, and is nothing at the edge of the wing-tips themselves.

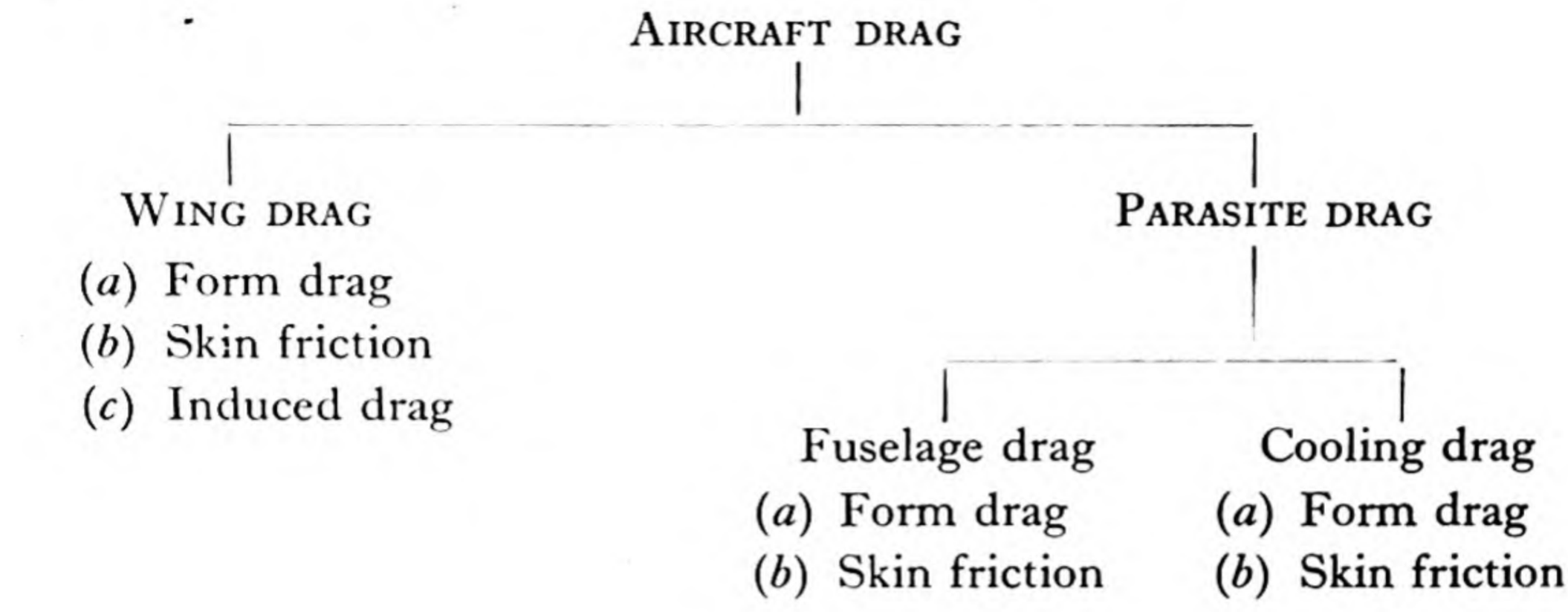
It can be shown that, although there can be no such thing as wings with infinite aspect ratio, yet the induced drag is decreased and the lift increased when the aspect ratio is made greater.

The theory of induced drag has been worked out and the formula for the amount of drag to be attributed to this cause has been obtained. This formula shows that the induced drag is inversely proportional to the aspect ratio. This agrees with what has already been written, namely, that the wing drag is smallest when the aspect ratio is large. In the second place, the formula shows clearly that for a given wing, the amount of induced drag will be greatest when the angle of attack is high and the aircraft is travelling slowly. In fact, whilst the induced drag may only contribute about 10 per cent to the total drag at normal speeds, at take-off, in steep climb, and at all times when the aircraft is flying slowly and the angle of attack of the wings is near stalling angle, the induced drag may be as high as 50 per cent of the whole.

Cooling Drag.

Cooling drag is often considered apart from the wing drag or the rest of the parasite drag. This is the drag caused by the devices used to keep the engine cool. The air-cooled radial engine was mentioned on p. 31; the cowlings used have greatly reduced the drag here. In the case of the liquid-cooled engine the design of the ducts through which the air is led is of great importance. Such an improvement has been effected in recent years that the total result of the duct and the radiator may be a forward-acting force instead of a drag. This apparent mystery is not so strange as it sounds. The explanation lies in the fact that the radiator and its duct are acting as a jet-propulsion device, giving a forward thrust more than sufficient to make up for their drag. A little more of the heat energy of the fuel is being stolen from it before it finally escapes, and turned to useful work.

The analysis of drag can be summarized as follows:



QUESTIONS

1. Show by means of a table the headings under which aircraft drag is usually analysed, and how these headings are subdivided into different types of drag.

State briefly how each type of drag may be reduced by altering the aircraft's design.

2. (*a*) What is meant by "fairing"? Give three examples of fairing with respect to aircraft.

(*b*) When does skin friction become important in aircraft design?

3. A flat circular disc is placed in front of the airstream from a wind-tunnel in order to measure the drag that it produces with its plane perpendicular to the airflow. It is then replaced by a streamline shape of the same frontal area with its axis parallel to the airflow.

(*a*) What change would you expect in the amount of drag?
(*b*) What is the difference in the airflow about the two bodies, and how does this account for the difference in the drag?
(*c*) Give a list of three parts of the aircraft where the results of this experiment have been applied.

4. By fairing and improved streamlining of the fuselage, the total drag of an aircraft is reduced without any appreciable alteration in weight. What effect, if any, will this have on the following factors?

(*a*) The maximum value of the ratio Lift/Drag.
(*b*) The wing loading.
(*c*) The stalling speed.
(*d*) The maximum speed.
(*e*) The landing speed.
(*f*) The range.

5. (*a*) The drag of a wing is usually analysed into three types. What are these?

(*b*) Taking each in turn, state the factors upon which the amount of drag from each depends for a wing of given size and shape.

CHAPTER III

The Aircraft in Level Flight

MEANING OF EQUILIBRIUM. THE FOUR MAIN FORCES. TRIM. PROBLEMS ON THE BALANCE OF AN AIRCRAFT IN LEVEL FLIGHT.

The Meaning of Equilibrium.

Although there may be only a small proportion of the time of flight during which the aircraft is flying level at constant speed, yet this is the fundamental condition for which the aircraft is designed, and is the easiest one to consider first.

Since the aircraft is not altering its speed or direction of motion it must be in a state of equilibrium under the action of the forces acting upon it. The term equilibrium has a precise and important meaning in mechanics. When a body is at rest it is in equilibrium; to start it moving a force must be applied. At rest, any forces on it cancel each other, or else there is no force acting on it at all, which, of course, amounts to the same thing. But the effect of an unbalanced extra force will always change this state of rest by *accelerating* the body, and the acceleration will continue just as long as the force continues to be applied, in the direction in which the force is acting.

What happens, now, if the force is discontinued? The body does not immediately stop moving. What does happen is that the acceleration ceases, and the body no longer continues to gain speed. We have now a state of affairs in which the body continues at constant speed in a straight line. This condition is also one in which either there are no forces acting, or the forces balance each other; there is no unbalanced external force to cause the body to change velocity, and so its velocity remains constant.

In order to bring the body to a standstill a force must be applied in the opposite direction. The effect of such a retarding force will cause a slowing down, equivalent to an acceleration in a direction opposite to the body's motion. It will continue to slow down as long as the force is applied, and will reverse its direction of motion if the force is applied long enough.

All this is an attempt to explain what is meant by " equilibrium ". In equilibrium forces are balanced, and equivalent to no force at all. Under these conditions the body may *either* be at rest, *or* moving at steady speed in a straight line.

If the body either gains or loses speed, it is no longer in equilibrium. Such a state of affairs can only be brought about by the application of an external force, as shown in fig. 24.

This is one of the three fundamental laws of mechanics first clearly stated by Sir Isaac Newton in his famous *Principia*. Translated from the original Latin, Newton's statement reads: " A body continues in a state of rest or uniform motion in a straight line unless constrained to alter that state by outward impressed force."

Most people agree that this is a reasonable supposition for bodies at rest, but are not so easily persuaded that the other part is true. The trouble about trying to verify this law for a body in motion is

Fig. 24.—" A body continues in a state of rest or uniform motion in a straight line unless acted upon by a force."

that the experiment is usually spoilt by unwanted frictional forces. A heavy truck on rails obviously needs a strong push to start it moving, and an equally strong push in the opposite direction to stop it. In between, frictional forces neglected, it is in equilibrium, and moves at steady speed. The only forces acting on it are its weight downwards and an equal and opposite supporting force or " reaction " from the rails upwards. These balance one another and therefore " don't count ". The reaction from the rails undoubtedly exists, and without it the truck would drop vertically, just as the occupant of a chair will descend if the reaction from his chair vanishes owing to its sudden removal by some mischievous person.

The Four Main Forces.

There are four main forces acting on the aircraft. They are:

1. *The Lift* acting vertically upwards in this particular instance because the flight is along a horizontal line, and acting through the centre of pressure.

2. *The Weight* acting vertically downwards from the centre of gravity.
3. *The Thrust* acting forwards along the propeller shaft, usually horizontally.
4. *The Drag* of the whole aircraft, acting, in this particular case, horizontally backwards along a line that can be called the line of drag.

Since the aircraft is not altering its speed or its direction of motion, it is in a state of equilibrium just as surely as if it were not moving at all (see fig. 25), and in this state the forces acting on it must balance.

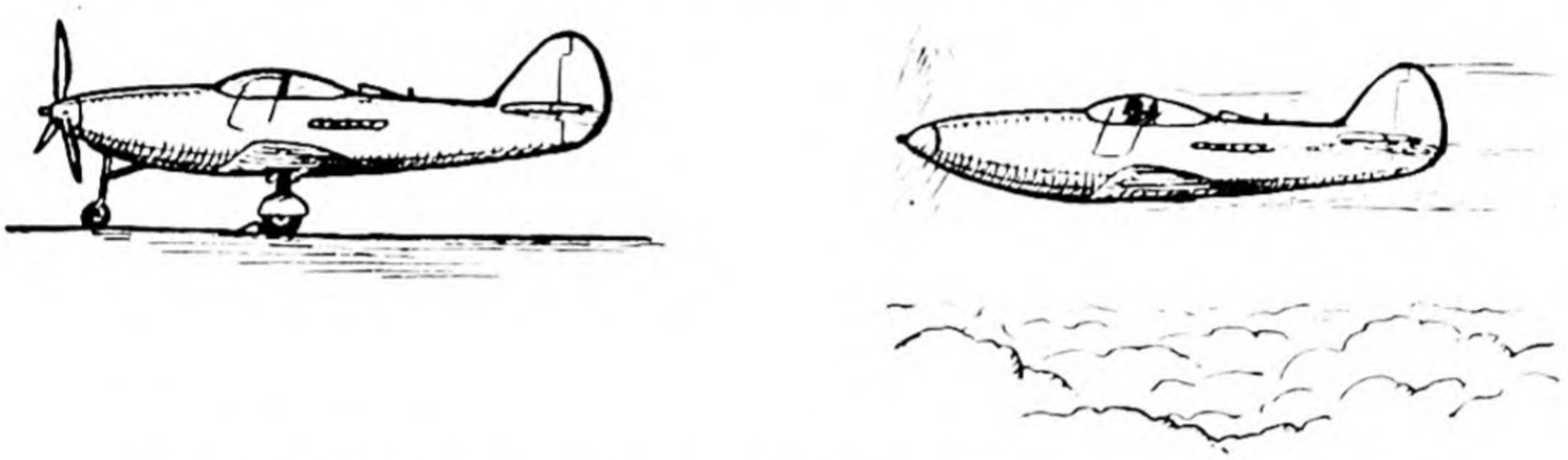


Fig. 25.—Two cases of equilibrium due to balanced forces; at rest and in level flight at constant speed

This means that:

(*a*) *The Lift* (*L*) *must equal the Weight* (*W*).

An aircraft at rest on the ground is in equilibrium, like the truck, under the balanced action of its weight and an equal supporting force where the ground pushes upwards on the wheels. In steady flight the supporting force is provided by the lift from the wings. If the lift is a little more than the weight, the aircraft will begin to gain height, and if the lift is less than the weight, then the aircraft will commence accelerating downwards. For level flight the values of *L* and *W* must be equal.

(*b*) *The Thrust* (*T*) *is exactly equal to the Drag* (*D*).

If the thrust is greater than the drag, then the aircraft will be gaining speed or, as it is usually put, accelerating, and if the reverse is the case, then the aircraft will be slowing down. Equilibrium means going on doing the same thing. Again it may be difficult to convince some people of this restatement of part of Newton's first law of motion, for it leads logically to the conclusion that if there were no drag, the aircraft would maintain its speed through the air with no propeller at all. This is quite true, and if only there *were* no drag,

the propeller would only be needed to accelerate the aircraft in the first place; once the desired speed had been attained, the propeller would not be needed, except of course in reverse, to pull the aircraft up at the end of its journey!

(*c*) There is a third condition for equilibrium beside the two already mentioned. It is this: that *there must be no twisting action from the forces.* It is quite possible to fulfil the first two conditions without fulfilling the third, but although the aircraft would not gain or lose height, and although it would not gain or lose speed, it would turn over in the air.

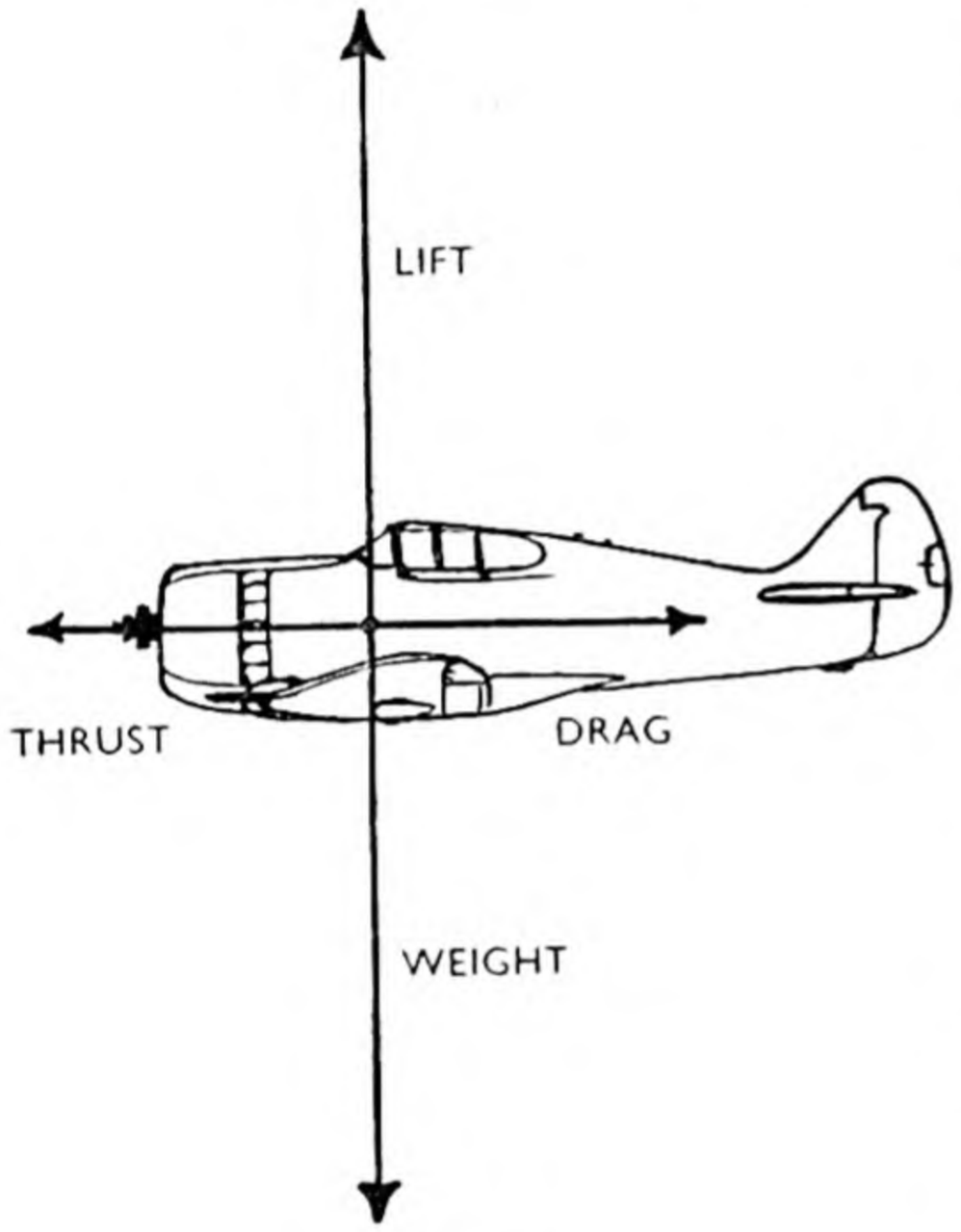


Fig. 26

One way of avoiding any twisting action would be to have the four forces acting through one point, as shown in fig. 26.

With an aircraft weighing 10,000 lb., L and W would both be 10,000 lb. Flying with the wings at the best angle of attack, the ratio D to L might be as high as 20 for the wings alone, but with parasite drag added to wing drag this value would be reduced to about 10. Reasonable values for T and D would therefore be 1000 lb. each.

It would, however, be impossible to arrange this simple solution for other than one particular set of conditions; one speed, one distribution of the weight, and one flight path, for:

(*a*) the Centre of Gravity (C.G.), the point from which the weight of the aircraft acts, will move if the crew alter their positions, or with alteration of bomb or petrol load;
(*b*) the Centre of Pressure is known to move with the alteration in the attitude of the aircraft which will be necessary for any alteration in speed;
(*c*) the position of the line of drag will alter whenever the attitude of the aircraft is changed;
(*d*) the line of action of the propeller thrust will alter slightly in angle whenever the attitude of the aircraft is changed.

For these reasons it becomes necessary to have some means at

the disposal of the pilot for counteracting any turning action that the four principal forces might have. The tailplane and elevator provide a small extra force up or down that will take care of any lack of equilibrium in the other forces. The position of the tailplane and elevator at some distance from the centre of gravity of the aeroplane gives this force considerable leverage and means that only comparatively small forces need to be introduced there.

The arrangement of forces illustrated (fig. 27) is one commonly met with in the modern aircraft. The thrust and drag act almost

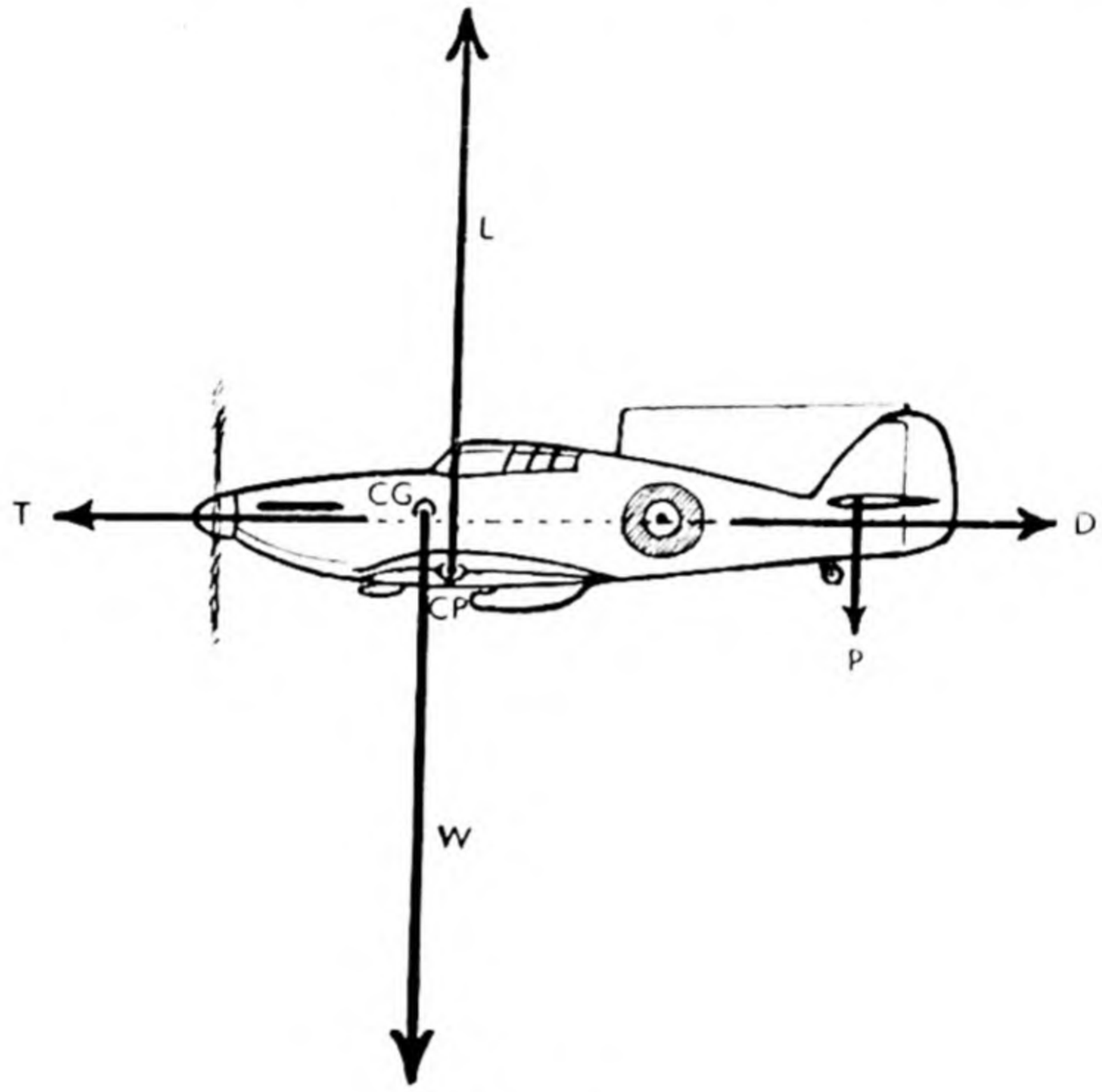


Fig. 27

along one line, and since they are equal, they produce no turning effect about the centre of gravity. The centre of pressure lies a short distance behind the centre of gravity and, therefore, the lift force introduces a turning effect about this point which tends to make the nose of the aircraft drop. The download on the tailplane and elevator maintains equilibrium by introducing a turning effect about the centre of gravity in the opposite sense.

In this case the conditions for equilibrium can be stated as follows:

1. Lift equals Weight (plus any down load on the tailplane).
2. Thrust equals Drag.
3. The forces as a whole exert no turning effect about the centre of gravity.

In order that it may give this "downward lift" the tailplane must lie at a negative angle of attack to the relative wind, yet often, when the aircraft is examined, the tailplane would seem to be horizontal in level flight at normal speeds. This contradiction is only apparent, for owing to the downwash from the main planes, the relative wind that strikes the tailplane is not, for once, the direction of motion reversed, and it passes the tailplane in such a way as to give an effective angle of attack that is negative. This is illustrated in fig. 28.

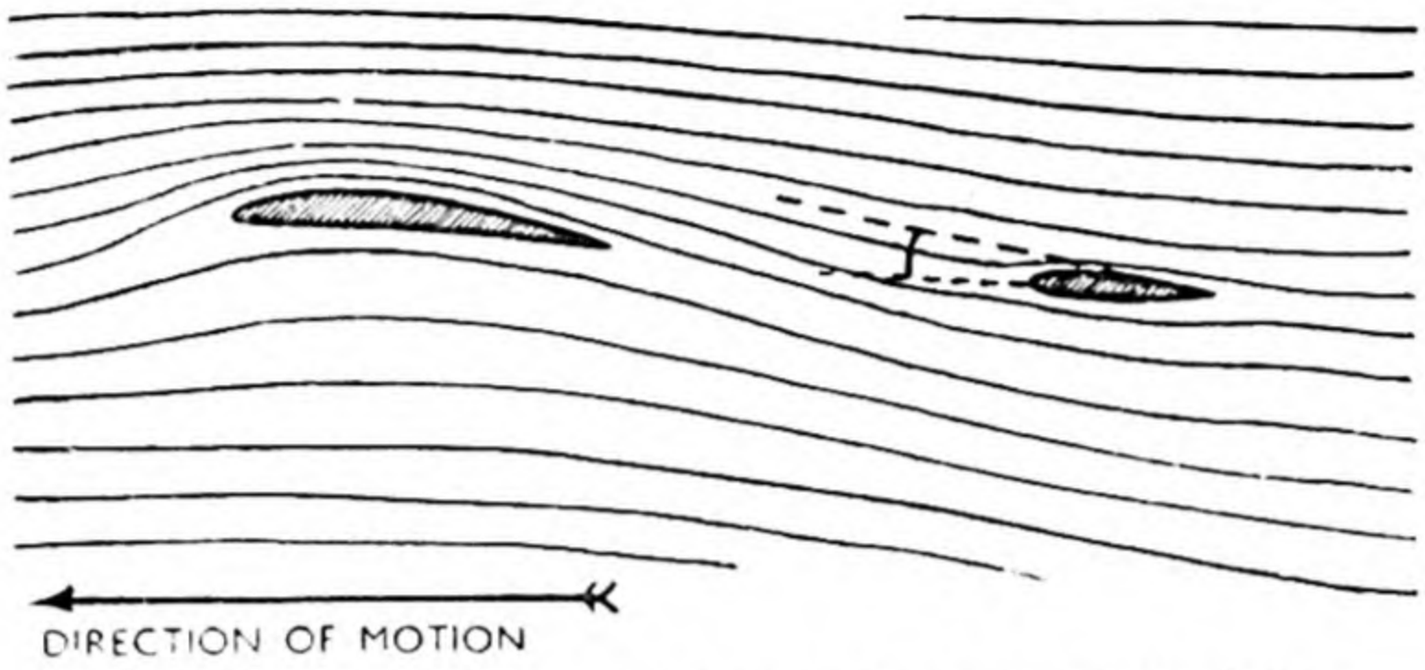


Fig. 28.—Effect of downwash on angle of attack of tailplane

Trim.

It has already been emphasized that although the designer might arrange for the forces acting on the aircraft to balance exactly when the aircraft is flying at a particular attitude, and with a particular distribution and magnitude of the load, change in any of these factors would immediately upset the equilibrium, and the aircraft would need to be retrimmed.

The adjustable tailplane provides one solution of this difficulty, and is still retained on some aircraft where the unusually wide range of attitudes for which it is required to compensate make this method of trimming necessary. The tailplane is capable of being rotated about a hinge so that the angle of attack can be varied.

The pilot may use the elevator, the hinged control surface behind the tailplane, to do the same thing. Suppose, for instance, that the navigator moves to the nose of the aircraft to take a drift; the aircraft will be nose-heavy, because the C.G. is now farther forward than it was before. If the pilot eases the control column back, the elevator will be held up and the download on the tailplane and elevator will be increased, thus restoring the balance. The same thing will be needed if the attitude of the aircraft has to be adjusted for an alteration of speed (see (*b*), page 38).

The force on the control column is not great, but on long flights

it can be tiring, and the aircraft is easier to fly without this continuous pressure on the " stick ". The adjustable tailplane was one method of attaining this end, but a neater way is now generally used. This is by the use of *trim tabs*, which, once correctly adjusted by the pilot, will hold the elevator in the required position, so that the aircraft will fly " hands off ". The full explanation of this trim tab must wait until controls are discussed (p. 84).

Problems on the Balance of an Aircraft in Level Flight.

A clearer insight into the question of the aircraft's balance in level flight may be gained by actually calculating the size of the forces involved. This may be done by the application of the law of moments. The rest of this chapter is devoted to explaining this law and working out some examples of its application to aircraft.

It is common knowledge that two boys can play at see-saw although there may be a great difference between their weights; the heavier boy gets nearer the centre or the small boy moves farther away. What matters is not that the two weights on either end of the see-saw shall be equal, but that the turning effect of each shall be the same. This is clearly a matter not only of weights, but of distances of these weights from the fulcrum or turning point. It may be shown that when the two turning effects are equal, and the see-saw balances, the product of the weight (or force) and its perpendicular distance from the fulcrum is the same on both sides. This product " force $\times$ distance " measures the turning effect a force exerts about a fulcrum, and is called the *moment* of the force.

In fig. 29 the clockwise moment is 50×4 lb.-ft. $= 200$ lb.-ft. This is equalled by the anticlockwise moment of $80 \times 2\frac{1}{2}$ lb.-ft. $=$ 200 lb.-ft.

Another fact may be deduced from this example, namely that, since the see-saw is in equilibrium, the downward forces must be balanced by an equal upward force: this is, of course, provided by the reaction at the support. The log must therefore be pushing upwards on the plank with the force of 130 lb. wt., and there are therefore three forces acting, and not, as might seem at first sight, only two.

Now these three forces have no twisting action about any point, and it may be shown that, with due regard paid to whether the moments are clockwise or anticlockwise, *the algebraic sum of the moments of these forces is zero about any point in the plane of the forces.*

The case of the aircraft illustrated in fig. 27 is similar: the supporting force, or lift, must equal the sum of the weight of the aircraft

and the download on the tailplane. Thus, if the aircraft weighs 6000 lb. and the download is 50 lb., then Lift is given by

$$\begin{aligned} L &= W + P \\ &= 6000 + 50 \\ &= 6050 \text{ lb.} \end{aligned}$$

What must be the distance between the Lift and Weight, if the perpendicular distance from the Centre of Pressure to the download

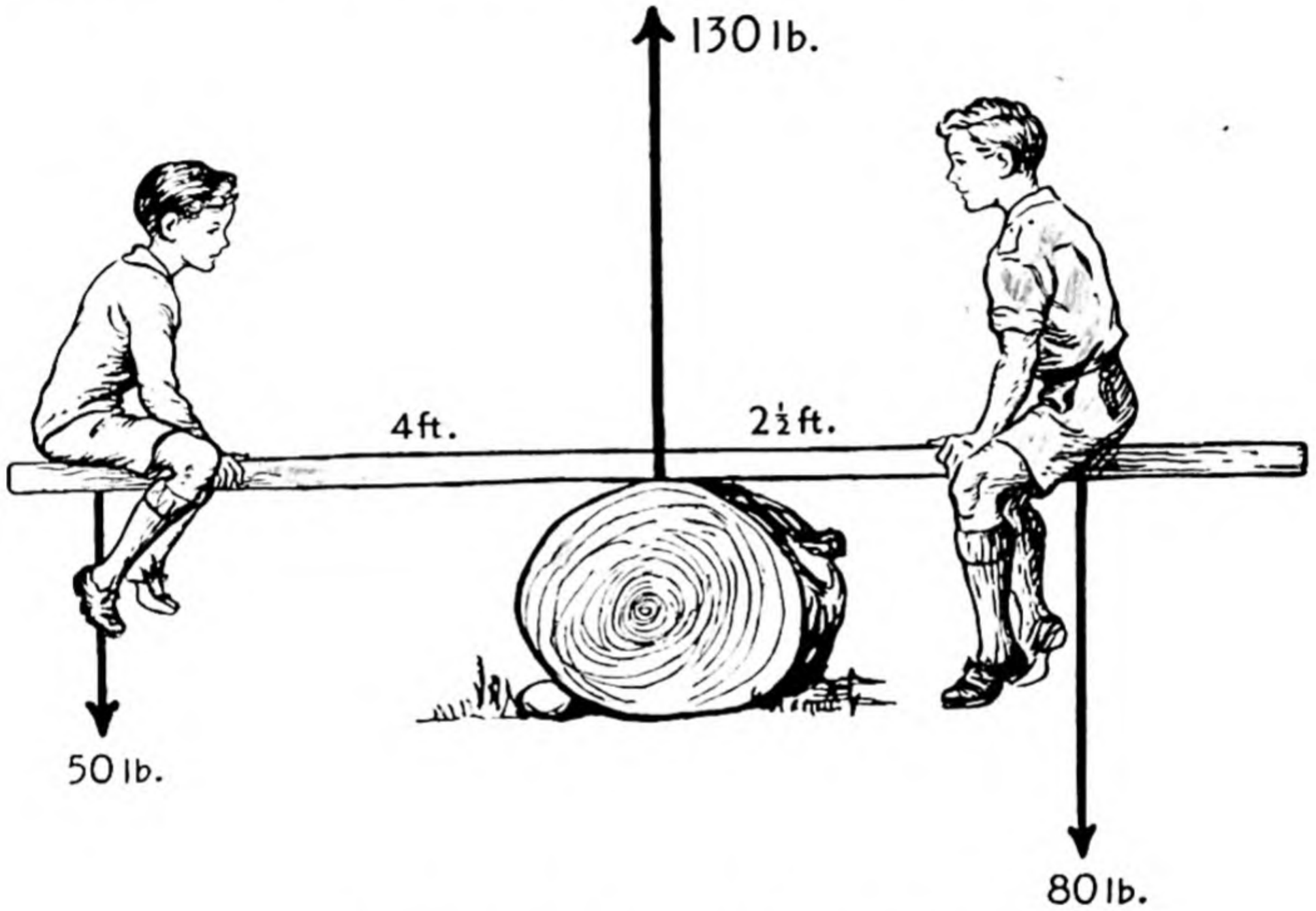


Fig. 29.—Illustrating the law of moments

is 20 ft.? Treating the Centre of Pressure as a fulcrum, and calling the unknown distance X ft.:

$$\begin{aligned} \text{Anticlockwise moment} &= \text{Clockwise moment}, \\ 6000 \times X &= 50 \times 20, \\ X &= \tfrac{1}{6} \text{ ft.} \end{aligned}$$

So that if the Centre of Gravity is 2 in. in front of the Centre of Pressure the aircraft will maintain its attitude of flight, since it will be in equilibrium under the action of the forces on it. The Thrust and Drag forces in this example have been neglected, since they were assumed to act along one line, and, therefore, have equal and opposite moments.

If the aircraft flies at a lower speed and therefore higher angle of attack of the wings, the Centre of Pressure will move forward towards the leading edge, and an upward force may be needed on the tailplane,

whilst at very high speeds, when the Centre of Pressure of the wings moves back, the aircraft will be flying with heavier download than that calculated in the example.

It has been stated that, so long as no force is neglected, any convenient place in the plane of the forces may be chosen and treated as the fulcrum. This will be made clear by reference to the example just investigated. If the Centre of Gravity is chosen as fulcrum, the Lift twists anticlockwise about this point, and the download clockwise. For finding the distance X we have therefore

$$\begin{aligned} \text{Anticlockwise moment} &= \text{Clockwise moment},\\ 6050 \times X &= (20 + X)\ 50,\\ 6050\ X &= 1000 + 50\ X,\\ X &= \tfrac{1}{6}\ \text{ft.}, \end{aligned}$$

and the same solution, 2 in., is obtained as before.

In the following worked examples the point about which moments are taken is chosen to give the simplest form of the equation upon which the solution is based. This point is usually the intersection of the line of action of two of the forces, which in this way are eliminated from the equation.

Example 1.—With biplanes it is possible to arrange the four principal forces as shown in fig. 30, for normal cruising speed.

If such an aircraft weighs 2400 lb., and $\frac{L}{D}$ at cruising speed is 8, how far behind the Centre of Gravity is the Centre of Pressure if the Drag line lies 1 ft. above the line of Thrust?

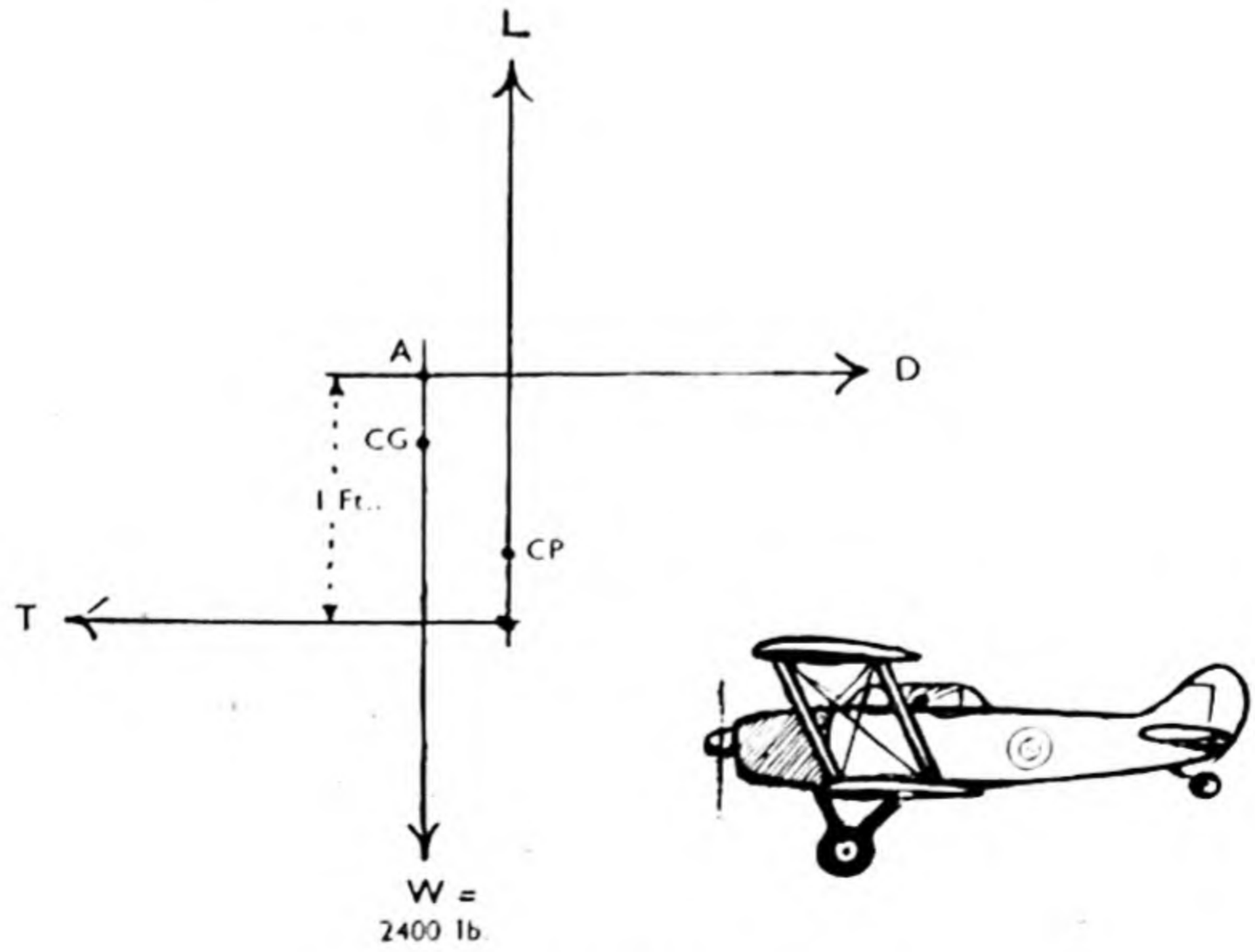


Fig. 30

Solution.—Let X be the required distance.

$$\text{First} \qquad L = 2400 \text{ lb.},$$
$$T = D = 2400/8 = 300 \text{ lb.}$$

Now taking moments about the point A:

$$\text{Anticlockwise moment} = \text{Clockwise moment},$$
$$L \times X = T \times 1,$$
$$2400\,X = 300,$$
$$X = \tfrac{1}{8} \text{ ft.} = 1\tfrac{1}{2} \text{ in.}$$

This is an ideally simple way of producing equilibrium, and all the load supported is useful weight, for no payload is sacrificed because there is a tail download to be lifted. If, however, this arrangement is investigated further, it is seen that it is not always a practical solution of the problem of balancing the forces on the aircraft, for if the Centre of Pressure lies only 6 in. from the position it occupies in this case, the drag line must be 5 ft. above the propeller shaft!

Example 2.—In a flying-boat it is necessary to keep the engines and propellers well clear of the water, and so the Thrust line is usually high. In the case shown in fig. 31, Thrust lies 3 ft. above Drag, and Lift is 3 in. in front of Weight. Weight = 80,000 lb.; $\frac{L}{D}$ at cruising attitude = 9; the Centre of Pressure of the tailplane and elevator is 30 ft. behind the Centre of Gravity of the aircraft, measured horizontally.

What is the load on the tail under these circumstances?

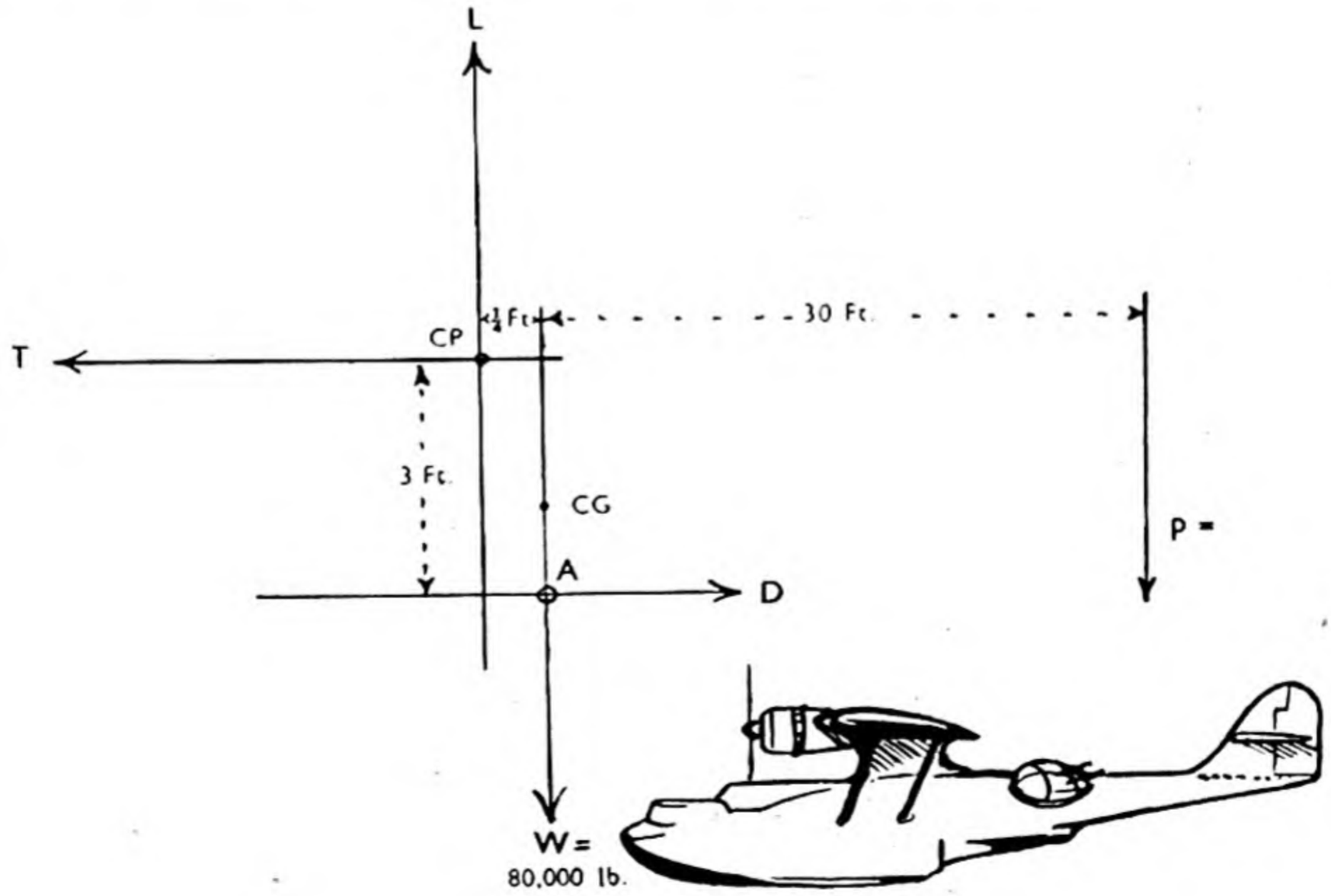


Fig. 31

Solution.—Assuming that the force P on the tail acts downwards:

$$L = 80{,}000 + P, \quad . \quad . \quad . \quad . \quad . \quad (1)$$
$$T = D = L/9. \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Taking moments about the point A:

$$\text{Anticlockwise moment} = \text{Clockwise moment},$$
$$3\,T = 30\,P + L/4,$$
$$3\,(L/9) = 30\,P + L/4,$$
$$L/3 - L/4 = 30\,P,$$
$$L/12 = 30\,P,$$
$$L = 360\,P,$$
$$80{,}000 + P = 360\,P,$$
$$P = \frac{80{,}000}{359}$$
$$= 223 \text{ lb. (approx.)}$$

A download (since P has turned out to be positive) is necessary, and the value must be approximately 223 lb.

QUESTIONS

1. (*a*) State the three conditions for equilibrium of an aircraft in straight and level flight.

(*b*) The navigator of an aircraft goes forward into the nose of the aircraft to take a drift. State which way the elevator trim tab is moved, and which way the elevator moves, as the pilot restores equilibrium.

2. (*a*) Show, by means of a sketch, the four principal forces acting on an aircraft in straight and level flight at a uniform speed. Mark on the diagram the centre of gravity and the centre of pressure of the aircraft.

(*b*) If the weight of the aircraft is 60,000 lb., the L/D ratio at the speed considered is 12, and there is no load on the tailplane, label the values of the forces in your diagram.

3. (*a*) What is meant by saying that the aircraft is in equilibrium?

(*b*) Name three different conditions in which the aircraft is in equilibrium.

(*c*) State the conditions for equilibrium in any one of these cases.

4. Diagram (*a*) (p. 46) shows a modern aircraft in equilibrium in level flight.

(*a*) Explain why the download on the tailplane is necessary.

(*b*) Explain why this download may exist even though the tailplane and elevator have a symmetrical cross-section, and are in line with the direction of motion.

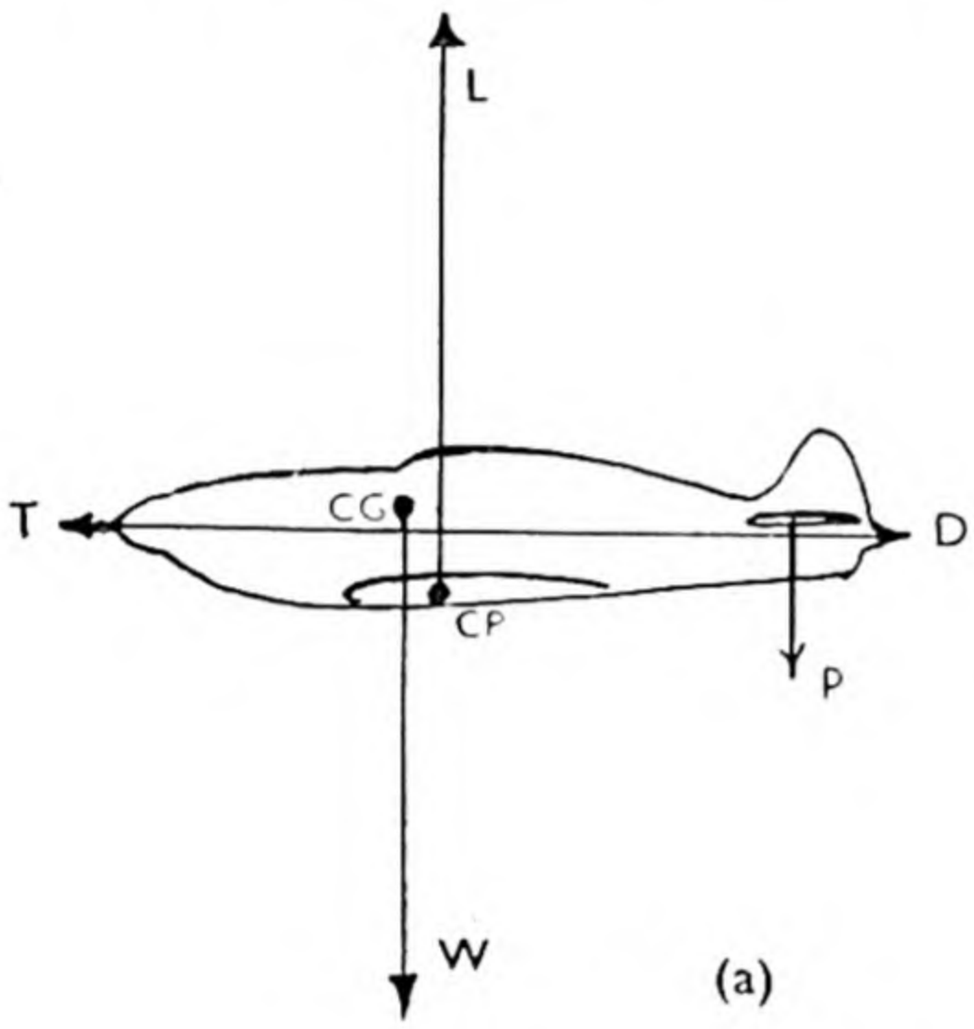
(*c*) Explain why the nose of the aircraft would drop if the engine failed.

5. (*a*) Show, by means of a diagram, the four principal forces acting on an aircraft in straight and level flight.

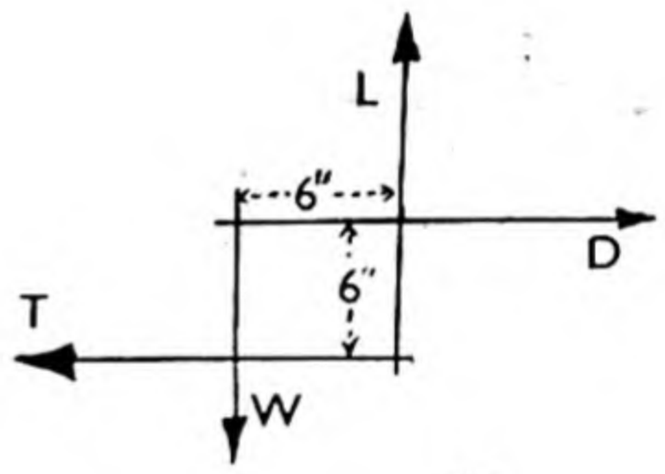
(*b*) If these are the only forces acting on the aircraft, state what relationship between them will give equilibrium.

(*c*) Give one reason why it is impossible to retain equilibrium without additional aid from the tailplane and elevator.

6. The drag line of a single-seater fighter aircraft is in line with the propeller shaft in level flight, whilst the lift acts along a line 3 in. behind the centre of gravity. If the aircraft weighs 10,000 lb., and the tail-load is 25 ft. behind the lift line, what is the load on the tailplane and elevator?



(a)



(b)

7. If the aircraft of Question 6 increases the angle of attack of the wings in order to maintain level flight at a lower speed, what adjustment must the pilot make to the tail-load, assuming that the lift line moves 2 in. forward?

8. In level flight the lift of an aircraft is acting 2 in. behind the centre of gravity, whilst the horizontal thrust line is 1 ft. from the drag line. There is no load on the tailplane.

(*a*) Which is higher, thrust or drag?

(*b*) What is the L/D ratio under these conditions?

9. In a twin-engined aircraft the principal forces in level flight at cruising speed are shown in diagram (*b*) above. The aircraft weighs 14,000 lb., and thrust is 1400 lb. If the centre of pressure of the tailplane and elevator is 30 ft. behind the lift line, find the values of the lift and the load on the tail.

10. A seaplane is flying straight and level. The horizontal thrust lies 2 ft. above the drag line. The centre of pressure of the tailplane and elevator is 60 ft. behind the centre of gravity, and the lift acts 6 in. in front of the centre of gravity. The loaded aircraft weighs 30 British tons, and L/D is 8 at the speed considered. Find the value of the tail-load.

CHAPTER IV

Gliding and Manœuvres

EQUILIBRIUM IN THE GLIDE. EFFECT OF WEIGHT IN GLIDING. EFFECT OF WIND IN GLIDING. EFFECT OF GLIDE ON STALLING SPEED. EFFECT OF USING ENGINE IN THE GLIDE. FLIGHT IN A CURVED PATH. STALLING SPEEDS IN TURNS AND PULL-OUT.

Equilibrium in the Glide.

The term gliding is taken to mean "flight maintained without the use of the engine". It is one of the conditions of flight in which the aircraft is in equilibrium, for the flight is along a straight line at steady speed; the forces acting on the aircraft are balanced, and there is no turning effect.

One of the four principal forces present in straight and level flight is absent in gliding, for *there is no thrust*. The problem is to investigate the conditions of the equilibrium under the action of the remaining three forces. To simplify matters, assume that there is no load on the tailplane.

This leaves three forces:

1. The Lift, acting at right angles to the flight path.
2. The Drag, acting backwards along the flight path.
3. The Weight, acting vertically downwards from the centre of gravity as usual.

Two of these forces are the components of the total reaction. It was found convenient at one time to split total reaction into lift and drag, but here, for the moment, we shall recombine them. This gives only two forces, the total reaction and the weight. In order to produce equilibrium with two forces, they must be equal in strength, and acting in opposite directions along the same straight line, like two teams holding each other in a tug-of-war. This determines the total reaction; it must always be vertical and equal to the weight, whatever the attitude of the glide.

If, now, the total reaction is split up again into its lift and drag components as shown in fig. 32, certain very interesting facts can be deduced from the geometry of the figure that have to do with the practical aspects of gliding.

The angle marked θ in the diagram is also the angle between the

horizontal and the glide path, and is called the *angle of glide*. The size of this angle depends on the ratio of the two sides of the triangle whose lengths represent the lift and the drag. The third side, the total reaction, is always the same for the same aircraft. If the ratio of lift to drag is large, the angle is small; if the ratio of lift to drag is small, the angle is large. This is shown in fig. 33. Therefore, *the angle of glide depends on the ratio L/D for the aircraft and on nothing else.*

From the ordinary lift and drag curves that show how lift and drag vary with the angle of attack of the wing, a new curve may be

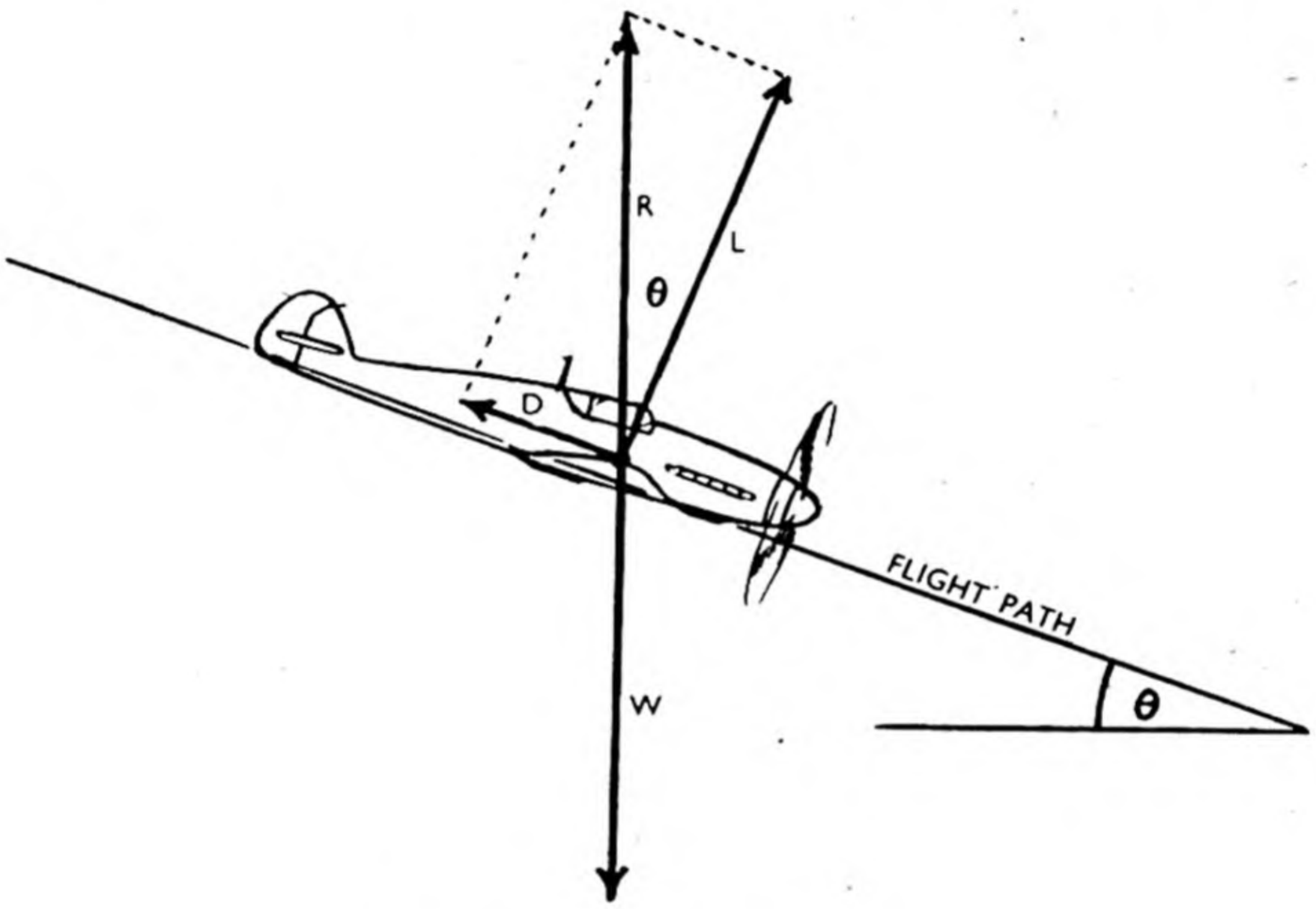


Fig. 32.—Geometry of the glide

plotted (fig. 34). This curve shows how the ratio L/D varies with the angle of attack. It can be seen that L/D reaches a maximum at a small angle of attack, usually around four or five degrees, and for angles of attack either less or greater than this the value of L/D is smaller.

Now the pilot, by controlling the attitude of his aircraft, can vary the angle of attack. If he wishes to glide at the smallest possible angle to the ground, i.e. with the flattest angle of glide, he will adjust the angle of attack of the wing through the medium of the attitude of the aircraft, so that this angle will correspond to that giving the maximum L/D ratio. This is so important as to be worth while restating. The flattest angle of glide corresponds to the maximum L/D ratio. If the angle of attack is less than that which gives this maximum value, the glide will be steep and fast, and might be called a dive with power

off. It will be fast because the drag is small at small angles of attack, and the component of gravity acting along the flight path in place of the thrust is large.

If the nose of the aircraft is pulled up in a natural attempt to make the aircraft fly farther, *the only result will be, once more, a steeper glide*, for again the value of L/D will be reduced. Owing to the larger drag at high angles of attack, and to the fact that the glide will not be quite so steep as with the nose down, the speed of the glide will be slow.

The pilot has no instrument in the aircraft to tell him what is the angle of attack. How, then, does he determine the flattest angle of

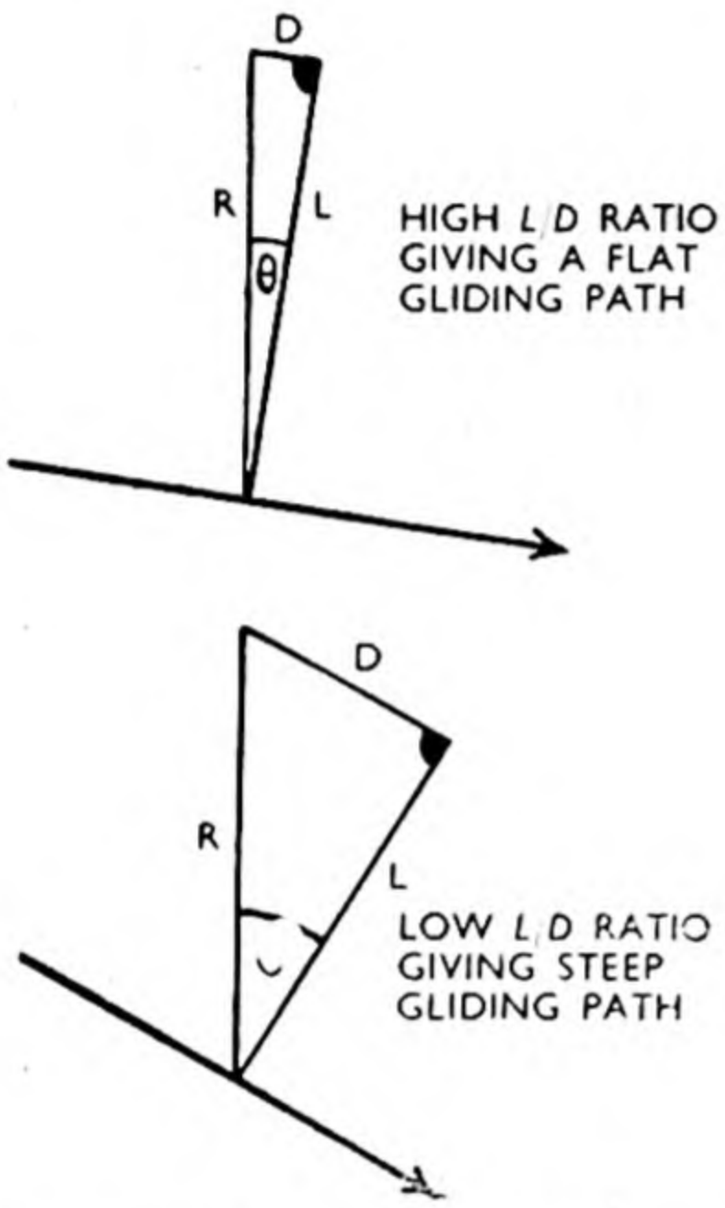


Fig. 33.—The angle of glide depends on the ratio L/D

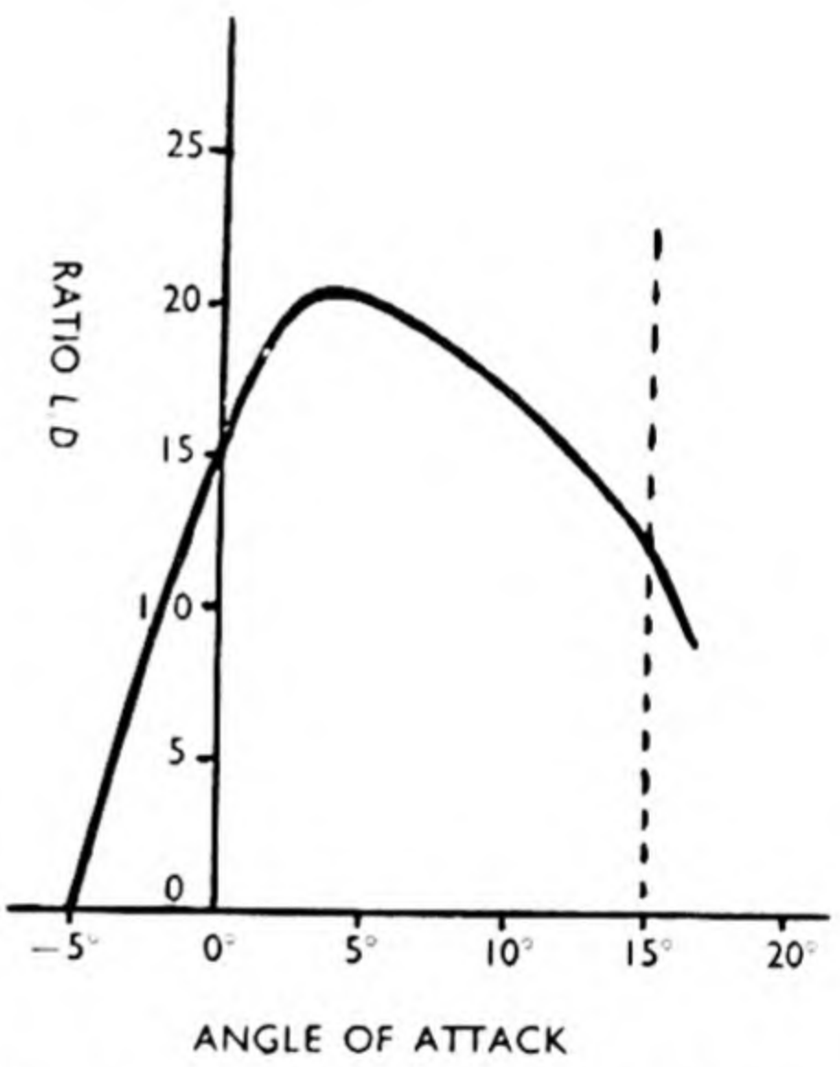


Fig. 34.—Graph showing how L/D varies with angle of attack

glide? *He watches his airspeed indicator*, for he knows that with each angle of glide there is a definite airspeed, and he trims the aircraft to fly at the airspeed given by the designer, corresponding to the best L/D ratio. Fig. 35 illustrates this.

The best ratio of L/D of which an aircraft is always capable is often taken as a measure of its aerodynamical efficiency, for it tells us how much lift (which the designer does want) and how little drag (which the designer does not want) go to make up the reaction from the aeroplane and its wings. The more efficient aircraft, from this point of view, will glide more flatly than the less efficient.

In trying to reach a landing field when the engine has failed, it is obviously an advantage to have the flattest possible angle of glide. The modern streamlined aircraft may have a ratio of L/D of 20 or

higher for the wings alone at their best angle of attack. When the drag of the fuselage is added, the overall ratio of L/D may be about 10, but the angle of attack is still the determining factor in fixing the highest value of L/D.

Suppose that the best L/D ratio of a particular aircraft is 12, and the engine fails 10 miles from the nearest landfall, at a height of 5000 ft. Will the aircraft reach the shore in still air? With a best value of L/D of 12, the aircraft can glide 12,000 ft. for a loss of height

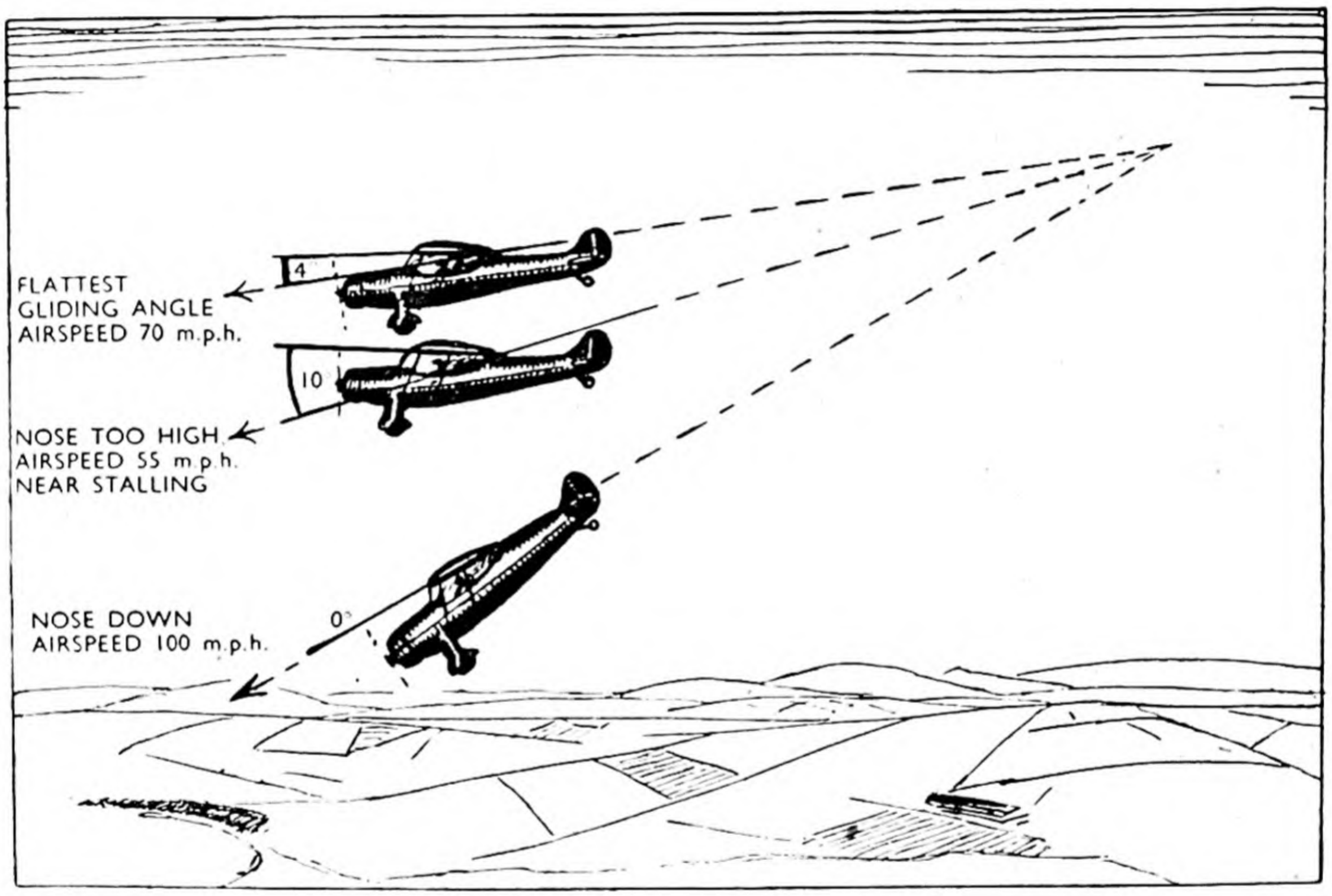


Fig. 35.—Effect of angle of attack on glide path

of 1000 ft., and for 5000 ft. loss in height can cover 60,000 ft. This is $\frac{60000}{5280}$ miles, nearly eleven and a half miles. The aircraft will reach the shore.

In landing the problem is not the same. Here the high value of L/D makes it difficult to get into the landing field. If the nose is put down, the glide is certainly steepened, but the speed will be dangerously high; and if the nose is pulled up, the glide will again be steepened, but the aircraft will be very near to stalling and a slight misjudgment or alteration of the wind would result in disaster. The pilot is forced back to the flatter angles of glide; the problem cannot be solved this way. A partial solution is to be found in the use of flaps.

Effect of Weight in Gliding.

An increase in the weight raises the speed of the glide but does not affect the angle. A larger weight requires a larger reaction to balance it, and this is obtained from an increase of speed. The actual values of the lift and the drag will be greater, but their ratio will fix the angle of glide.

Effect of Wind in Gliding.

The argument outlined applies to motion in still air. If there is a following wind, the aircraft will be carried a certain distance horizontally by the wind as it descends, and this will make any angle of glide slightly flatter. A head-wind has the opposite effect. (Fig. 36.)

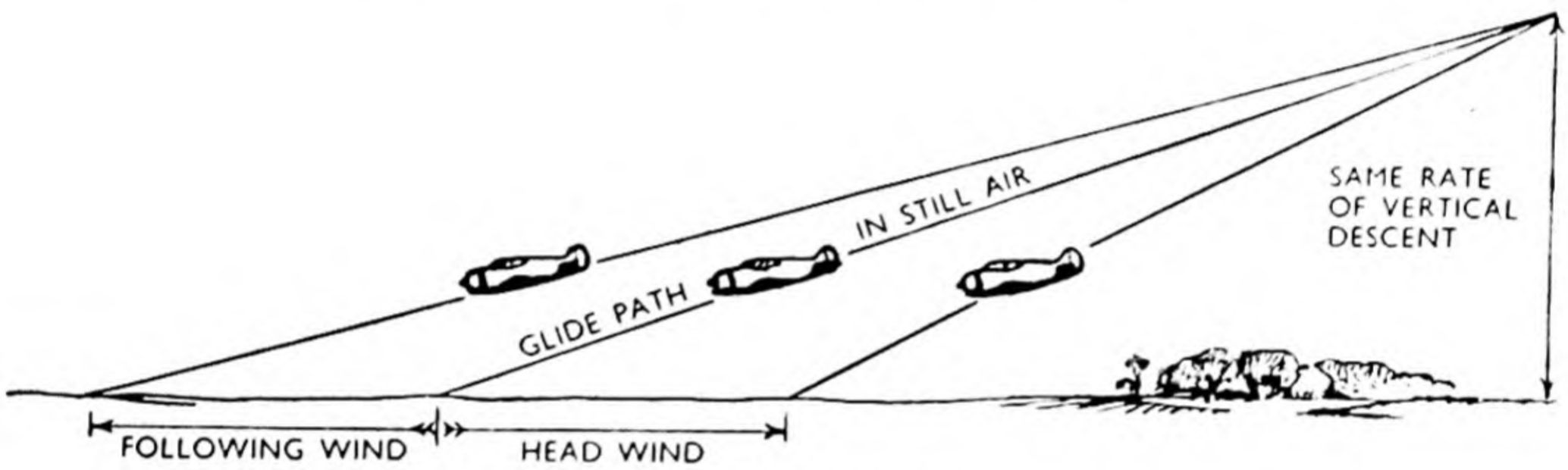


Fig. 36.—Effect of a wind on path of glide relative to ground

Effect of Glide on Stalling Speed.

The possibilities of the diagram showing forces in a glide are not yet exhausted. It can be seen from that diagram that the lift is slightly less than the weight, and therefore less than in horizontal flight. When the wing is at stalling angle this slightly reduced lift will require slightly less speed, and thus we discover that the stalling speed in steady glide is slightly lower than in level flight.

Effect of using Engine in the Glide.

If there is some thrust from the engine, the path of the aircraft will be flattened. We shall not investigate this in detail, but since power-assisted landings have become fashionable, the fact is mentioned. The judicious use of the throttle increases the range of angles within which the pilot may safely adjust the angle of glide.

FLIGHT IN A CURVED PATH

So far questions concerning the aircraft have dealt almost entirely with conditions of flight in which the aircraft has been in equilibrium and the forces on it balanced. The aircraft under these conditions is flying in a straight line. In a turn or a pull-out from a dive, the aircraft is not in equilibrium, for, in order to pull it from the straight line of flight, an extra unbalanced force is needed. This force acts towards the centre of the curved path, and an increase in the speed of

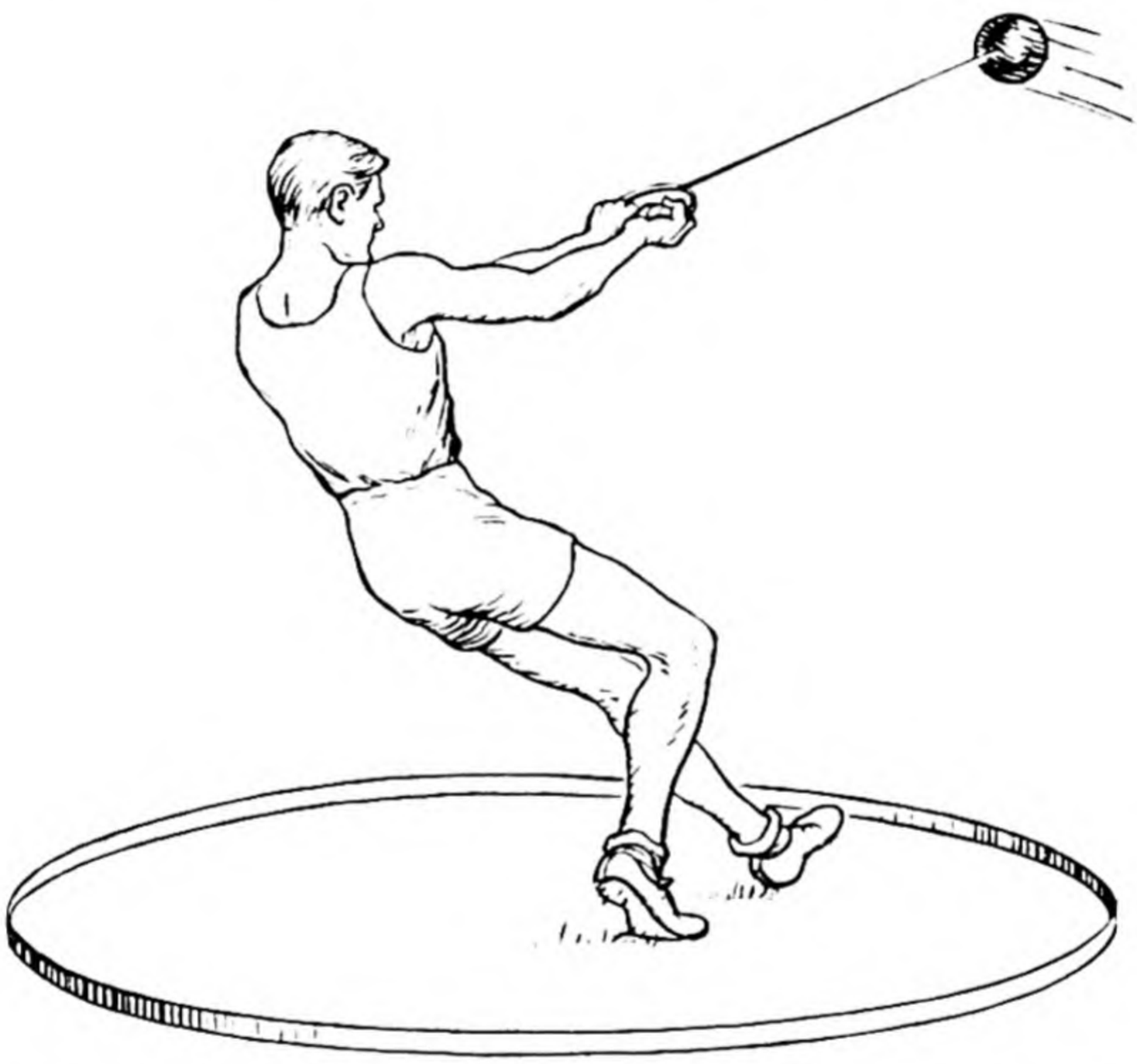


Fig. 37.—A force is required to make a body follow a circular path

the aircraft or a decrease in the radius of this curved path will need an increase in this force. This force is known as a centripetal force (fig. 37).

Although the existence of this force is not very well known, the reaction of the aircraft and of the pilot to it is the well-known centrifugal force.

An example may make this clear. When a car turns a corner, a force is necessary to pull it from its straight path. This force is provided by the grip of the road on the wheels. The car resists this force, and wants to go straight on. In fact, if the road is greasy it may do so. A passenger in the car also tends to go straight on unless pressure

from the side of the car provides a force to pull him around with it. If the car door is open, he will certainly continue along the same straight line, and be flung outwards from the car. However, it is to be hoped that the car door is closed and the force provided.

The passenger, naturally looking at things from his own point of view, thinks that he is pushing outwards on the side of the car. He is, of course, quite right. To every action there is an equal and opposite reaction, and if the car is pulling him round the corner, he is trying to push the car straight on. This reaction to the centripetal force, this apparent fling outwards, is what has been called a centrifugal force.

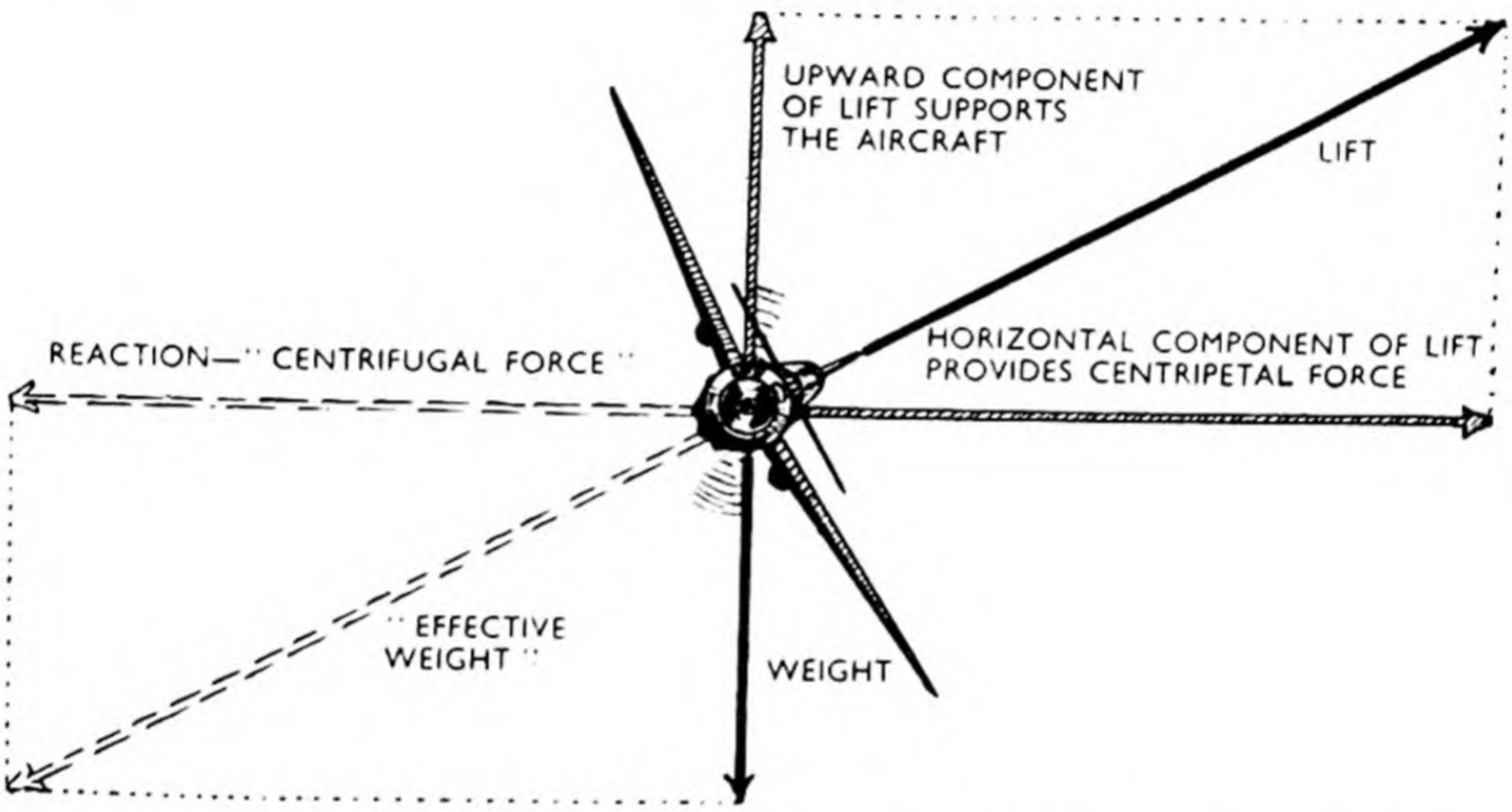


Fig. 38.—Showing the forces acting on an aircraft in a turn. The main forces are shown in heavy line; the lift may be split into two components shown by shaded lines.

In an aircraft, the force to pull the aircraft in a curved path is provided by banking the aircraft, and using part of the lift from the wings. The lift must therefore be greater than in level flight. This increased lift is provided, either by an increased angle of attack of the wings or by increased speed, or by a little of both.

The diagram (fig. 38) shows the forces acting on an aircraft in a turn, and it will be noticed that the lift may be split into that part which provides the centripetal force, i.e. the turning force, and that part which counterbalances the weight of the aircraft. It is quite obvious that an aircraft cannot maintain a 90° bank without loss in height, as there would then be no vertical component of the lift to hold the aircraft up.

It is sometimes more profitable to consider the whole thing from the point of view of the reaction, i.e. centrifugal force or fling outwards. This reaction, as shown in fig. 38, may be combined with the

normal weight to produce what may be called a new effective weight, or apparent weight. The new lift must lie in a direction opposite to this effective weight, and so for any given turn there is a correct angle of bank.

This effective weight acts as an increase in the weight of the aircraft, and so during the turn the wing-loading is temporarily higher than in straight and level flight.

Some interesting facts follow from this. Firstly, the aircraft must be sufficiently strong to withstand this extra wing-loading. The number of times the wing-loading is increased in comparison with its normal value is called the *Load Factor*. The aircraft will withstand load factors up to ten or more. A pilot is not so built, and usually " blacks out " at a load factor of about four or five. Meanwhile, his effective weight has increased in the same way as that of his aircraft, and the pilot who weighs 150 lb. may be stuck as firmly to his seat in a turn as though he weighed 600 lb. or more.

Stalling Speeds in Turns and Pull-out.

Most important of all is the effect on stalling speed. Suppose an aircraft begins a turn whilst travelling at its normal stalling speed. Extra lift is now needed, but the pilot cannot provide this by any increase in the angle of attack of the wings, since they are already at stalling angle. He must, therefore, provide the extra lift by an increase in speed. In other words, his minimum speed, i.e. his stalling speed, has increased. *Stalling speed is higher in a turn than in straight and level flight.* For instance, an aircraft which normally stalls at 60 m.p.h. will, during a steep turn at 75° angle of bank, have a stalling speed of 120 m.p.h. If the pilot allows his speed to drop below this value in the turn, the aircraft will stall. If the outer wing stalls first, the aircraft will flick over outwards into a spin; if (and this is less usual) the inner wing stalls first, the aircraft will turn over inwards as it drops. These are what are known as high-speed stalls.

The same argument is effective if the aircraft is pulling out from a dive. Sufficient lift must be provided to pull it into the curved path, and again the stalling speed increases. The faster the aeroplane is travelling and the sharper the curve attempted, the higher the stalling speed.

This is one good reason why a pilot should never attempt to turn back into the airfield if his aircraft suffers from engine failure immediately after take-off. There is not enough flying speed in hand to risk a turn.

QUESTIONS

1. (*a*) In still air, on what aerodynamic characteristic does the flattest angle of glide of an aircraft depend, and in what way?

(*b*) What is the effect, if any, on the gliding angle of throwing out of equipment to make the aircraft lighter?

(*c*) What is the effect, if any, on the glide path relative to the ground of a following wind?

(*d*) How does the pilot judge the flattest angle of glide?

2. (*a*) Why is an aircraft banked when turning?

(*b*) What will happen if the angle of bank is too great?

(*c*) Why is the stalling speed higher in the turn than in straight and level flight?

(*d*) Why is it impossible for an aircraft to make a vertically banked turn without losing height?

3. (*a*) When is a wing said to be stalled?

(*b*) What is the effect, if any, on the stalling angle of the wing of stalling in a steeply banked turn?

(*c*) What is the effect on the stalling speed of the aircraft of stalling from a steeply banked turn?

4. (*a*) Show by means of a diagram the forces acting on an aircraft in a steady glide.

(*b*) A pilot begins to flatten out from a steep glide. What happens to (1) the angle of attack, (2) to the glide path, and (3) to the airspeed, as the nose of the aircraft is gradually raised?

5. A glider (sailplane) usually has a very high aspect ratio.

(*a*) What does " aspect ratio " mean?

(*b*) What effect has the high aspect ratio on the aerodynamic qualities of the wing?

(*c*) How does this affect the angle of glide?

6. (*a*) What influence has an increased aspect ratio on the maximum lift/drag ratio of the wing?

(*b*) Does the maximum L/D ratio occur at a high or low angle of attack?

(*c*) What is the effect of lowering the undercarriage on the glide path, and why?

CHAPTER V

High-lift Devices

SLOTS: HOW THE SLOT WORKS. FLAPS. USE OF FLAPS IN APPROACH AND LANDING. USE OF FLAPS IN TAKE-OFF. USE OF FLAPS IN MANŒUVRES. AIR BRAKES. SPOILERS. WHEEL BRAKES AND TRICYCLE UNDERCARRIAGES.

Attempts have been made from time to time to increase the lift obtainable from a wing, with the main idea of reducing the landing speed. If it were possible to alter the area of the wing in flight, its smallest area could be used to give low drag for high-speed flying, and its largest area to give increased lift to reduce the minimum speed of flight.

It is sometimes stated that a wing so devised as to permit the angle of incidence to the fuselage to be varied would permit of a lower landing speed. This is of course quite false. All that would be accomplished would be that the aircraft would land with the fuselage at a different attitude, whilst the wings would be at their usual stalling angle. Only the visibility would be improved.

There are in general two devices in common use on aircraft for altering the characteristics in flight: namely, slots and flaps.

SLOTS (fig. 39)

These are narrow gaps along the leading edge of the wings formed by small auxiliary airfoils (slats) extending along the front edge of the wing. The gap is called the *slot*; a small auxiliary airfoil is called a *slat*. The results of such devices are shown in fig. 40 and are:

(*a*) The stalling angle of the wing is postponed for about another ten degrees, giving a stalling angle around 25°.

(*b*) The lift continues to increase until the new stalling angle is reached, at which point the maximum lift is 50 per cent to 100 per cent higher than the maximum lift at the normal stalling angle without the slot.

An aircraft can make use of this extra lift to reduce its minimum speed further. In other words, the stalling speed of the aircraft is reduced by the use of slots, and both landing and take-off speeds are less.

How the Slot Works.

It will be remembered that when a wing stalls, the airflow fails to follow the contour of the upper surface and, breaking away near the leading edge, becomes turbulent over the wing. The purpose of the

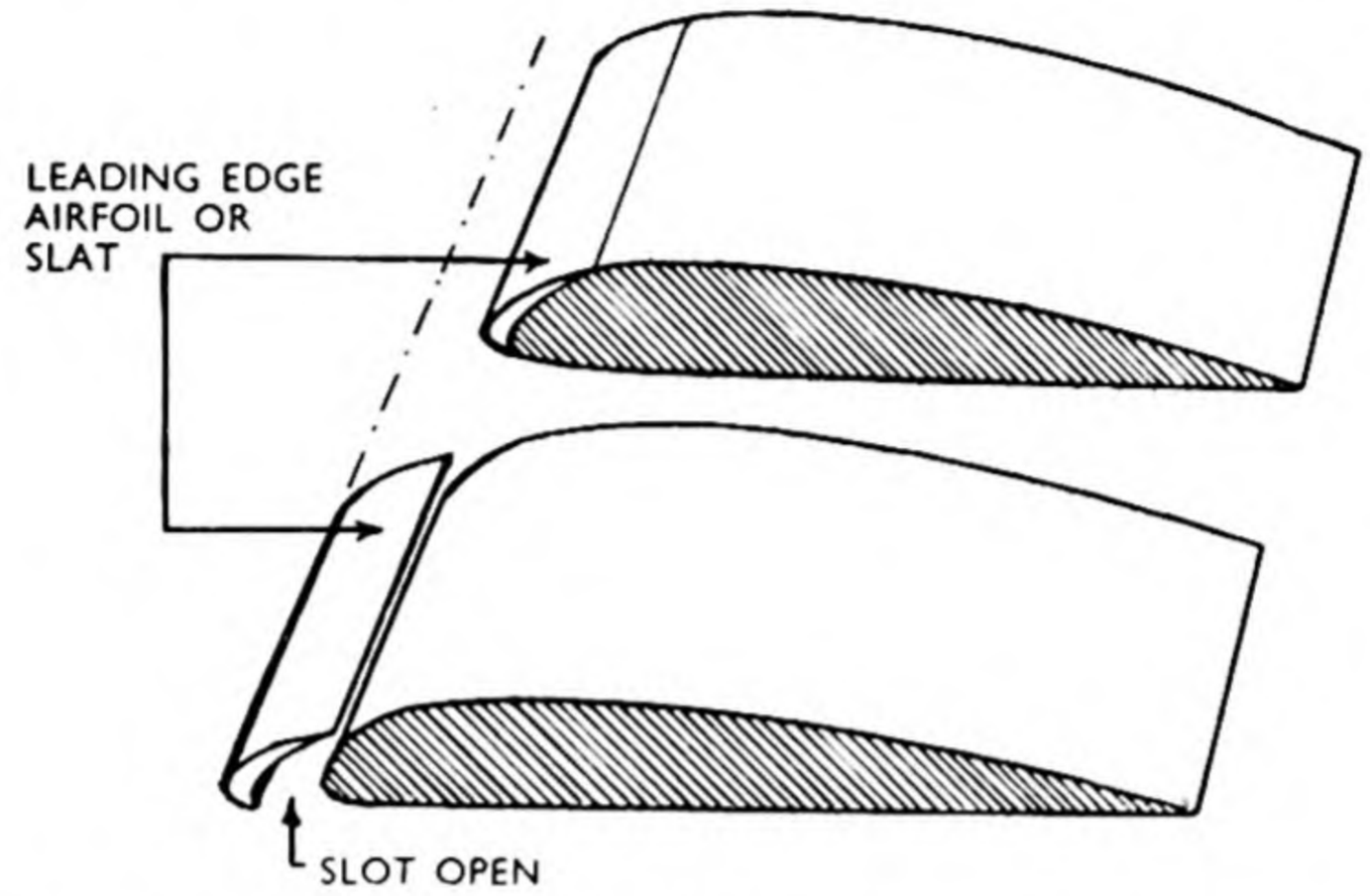


Fig 39.—Showing how an adjustable leading-edge slat becomes part of the wing when closed

slot is to prevent this by forcing the air to flow smoothly over the wing, so that it will continue to provide lift until the new stalling angle is reached. In fact, the slat acts as an airfoil whose angle of attack, relative to the upwash that strikes it, is less than its stalling

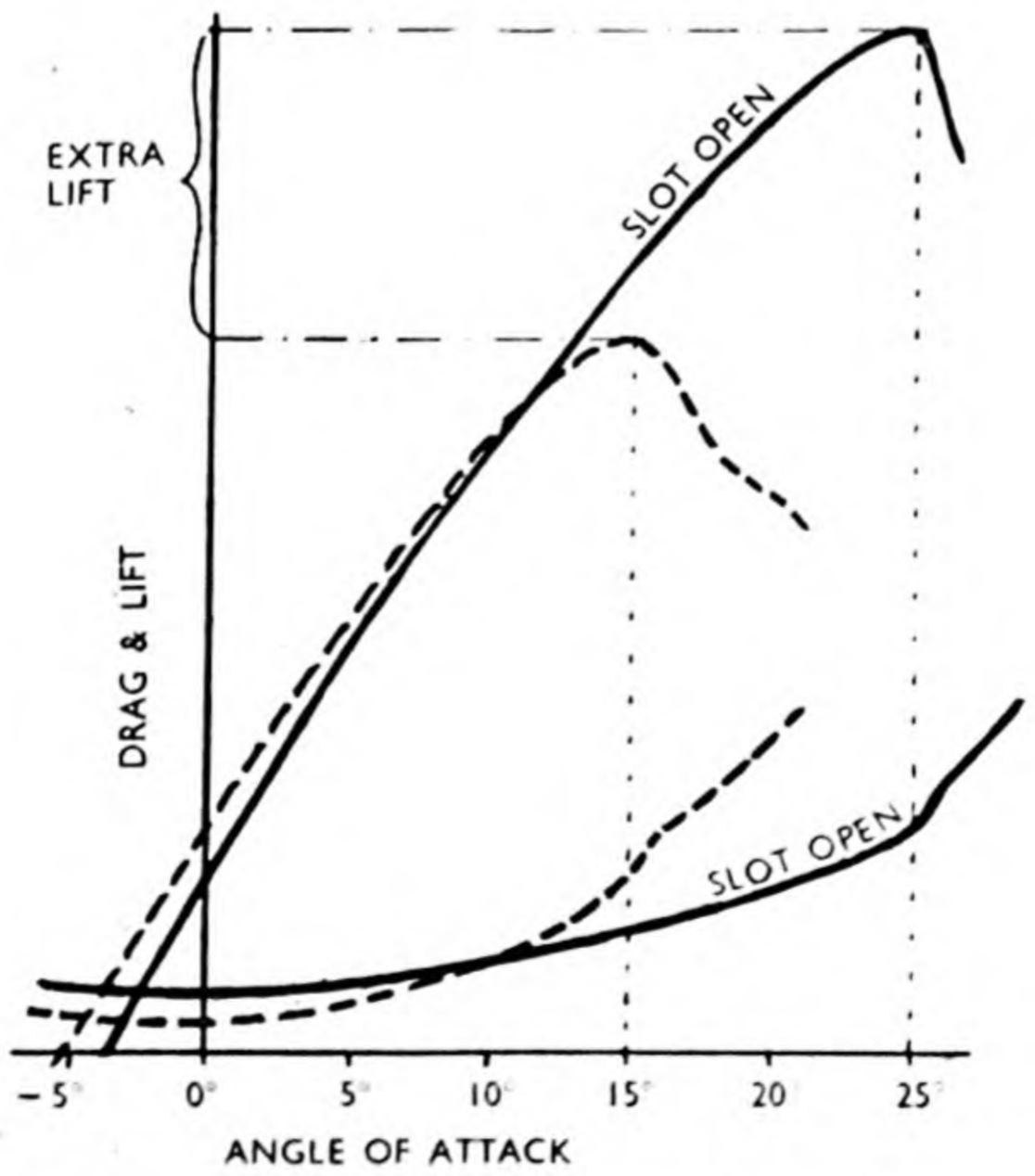


Fig. 40.—Graphs showing effect of slot on a wing

angle. The air, therefore, flows smoothly past the slat and its downwash helps the air around the leading edge of the wing. Fig. 41 shows the same wing at angle of 25° in the airflow, with and without a slot. The shape of the slot seems to be of some importance; it is much wider in front where the air enters than behind where it leaves. The air, accelerating through this constriction, seems to help in clearing away the stagnant air that would otherwise exist there.

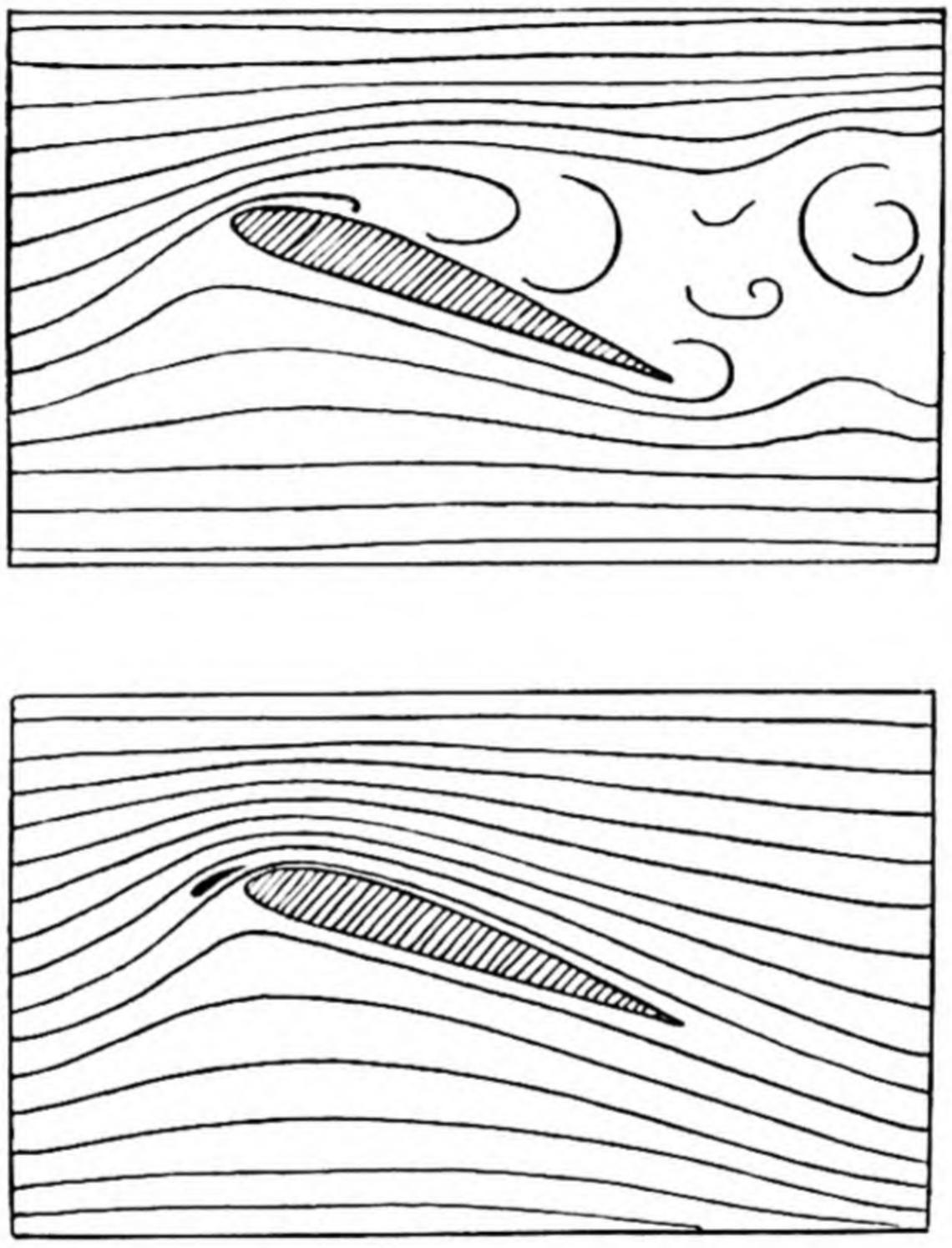


Fig. 41.—Showing the difference made by a leading-edge slot at angle of attack of 25°

If the slot remains open at small angles of attack, drag is greater than with the plain unslotted wing. Even when closed it is impossible to avoid some slight irregularities at the junction of the slat and the wing. For high speed, therefore, when the wing strikes the air at a small angle of attack, the slot offers no advantage; on the contrary, the extra drag puts it at a disadvantage when compared with the plain wing. This is why slots are seldom found in high-speed aircraft.

Slots may be:

(*a*) *Fixed*—when they are integral parts of the wing, and in effect are holes through the wing.

(*b*) *Operated by the pilot*—in this case, when closed, they form part of the wing, but hinge forward to leave a gap for slow speeds.

(*c*) *Automatic* (fig. 42)—these are particularly interesting. The slat lifts off near the stalling angle, pulled forward by the reduced pressure that builds up near the leading edge at high angles of attack.

The disadvantage of the slot as a high-lift device to give low landing speeds lies in the fact that abnormal angles of attack are needed to make use of them. Such angles of attack call for very high undercarriages, and give poor visibility for the pilot at a time when he particularly wishes to see the ground clearly.

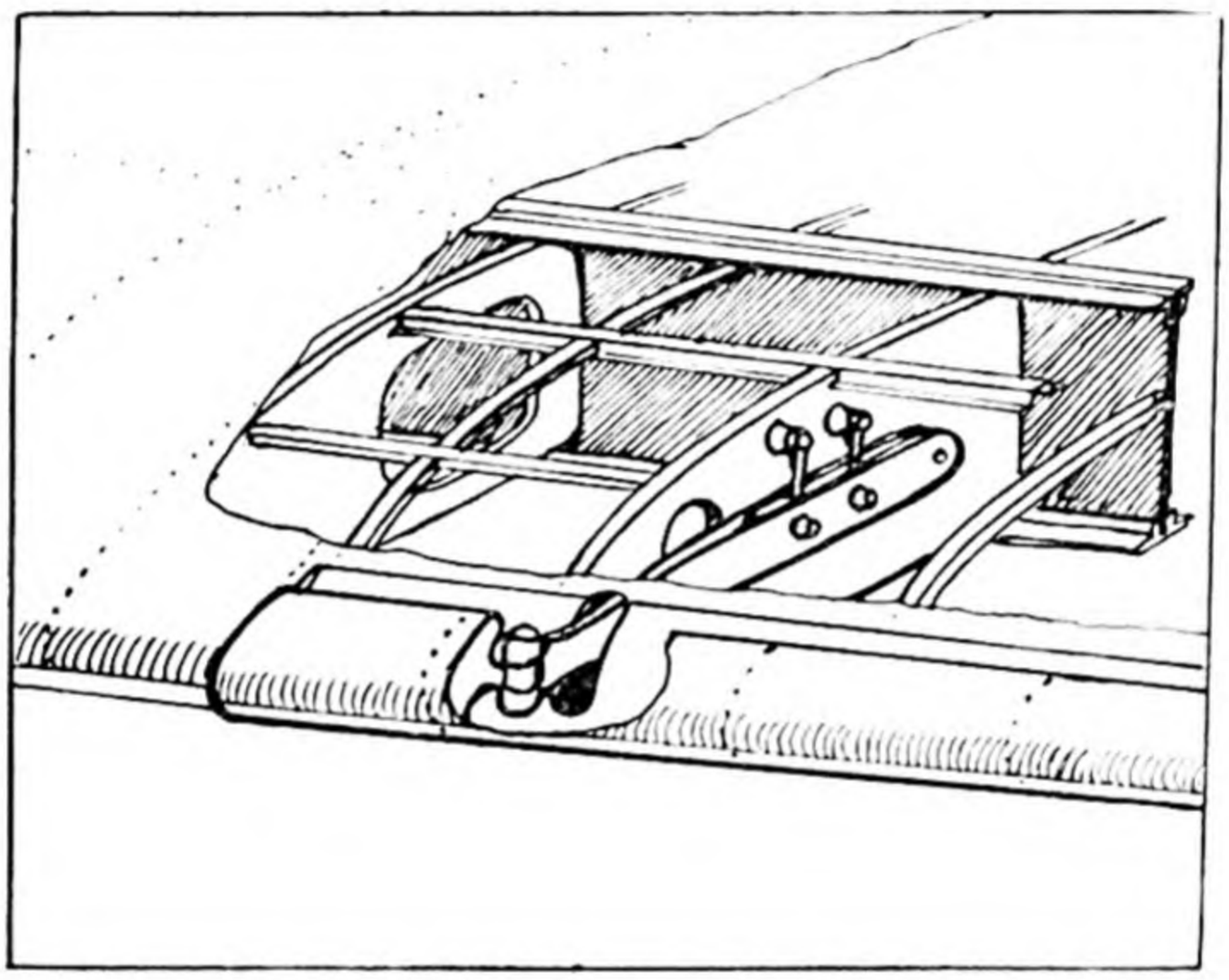


Fig. 42.—Automatic slot

For this reason, slots are not very widely used, except near the wing-tips. Wing-tip slots help to improve the lateral stability and control at slow speeds, but the way in which this is accomplished must be left until stability has been discussed (p. 78).

FLAPS

Flaps are hinged portions of the wing at the trailing edge between the ailerons and the wing roots. They originally constituted one more attempt to lower landing speeds, but their use has been greatly extended. Flaps of many and varied designs are to be found, and almost every aircraft is fitted with one type or another.

The diagram (fig. 43) shows in cross-section some of the types of flaps in common use. The first two might be termed variable camber flaps, since when they are lowered they have the effect of producing

a wing which is more highly curved or cambered. The split flap and the slotted flap also produce extra lift in a somewhat similar fashion. The last pair, Fowler and Gouge flaps, not only increase the camber of the wing, but also its area.

It is best to consider first the effect of the flap on the lift, drag, and the ratio of drag to lift. For any given angle of attack drag increases steadily as a flap is lowered to its full extent. Lift, on the

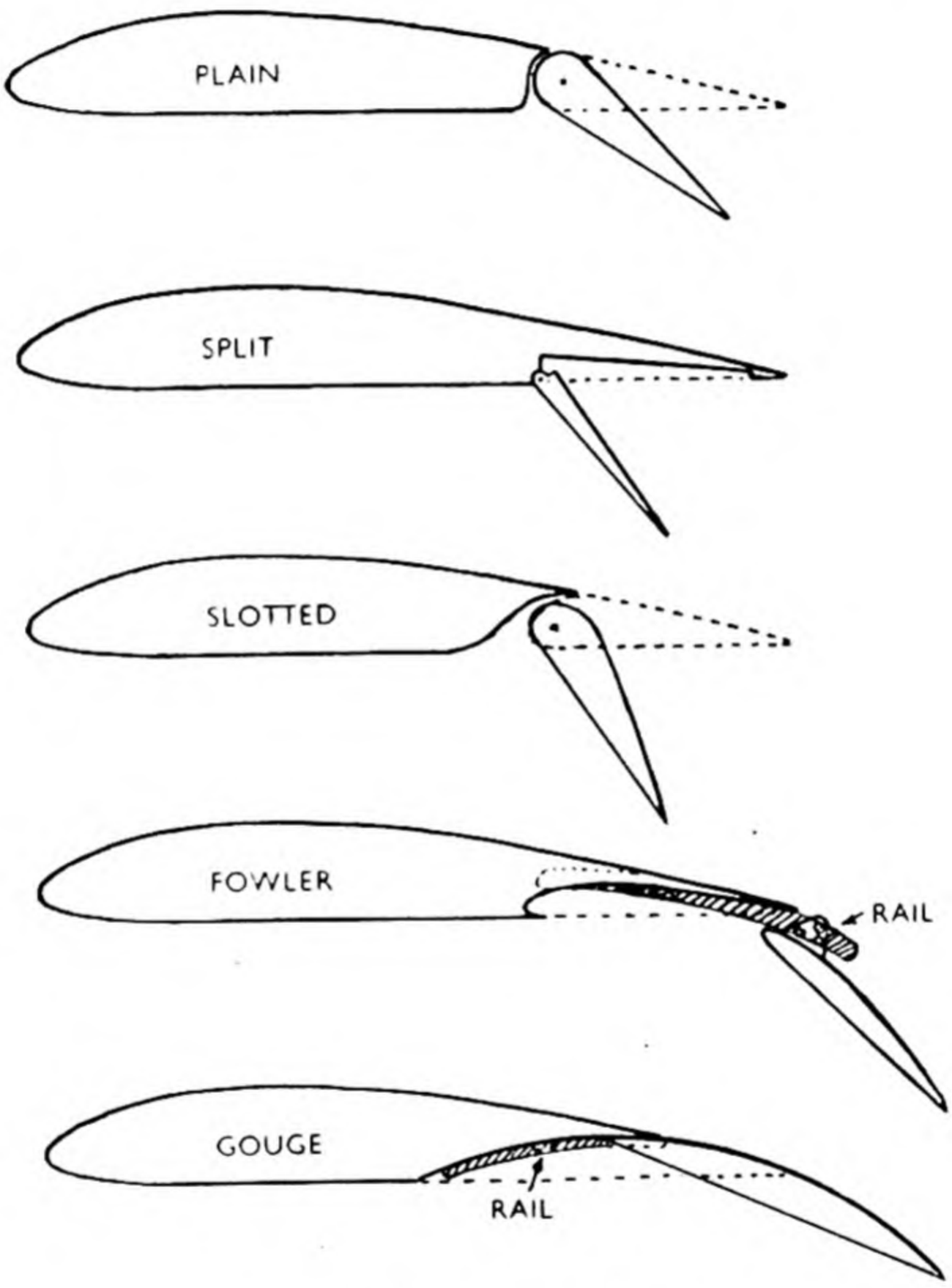


Fig. 43.—Types of flap

other hand, while increasing during the first 30° or so of flap angle, increases less in the next 30°, and during the last part of its travel the flap has no appreciable effect on lift. In fact, there is sometimes a slight decrease. The graph of fig. 43*a* summarizes the aerodynamical effects of a flap.

Although both L and D increase, the ratio L/D usually decreases right from the start. Fowler and Gouge flaps possibly give an increased value of L/D during the first few degrees of their travel.

Use of Flaps in Approach and Landing (fig. 44).

The changes in the aerodynamic characteristics of the wing made possible by the flaps are fully utilized in approach and landing. The flaps are lowered, with the following results:

(*a*) The glide path is steeper, due to the lower L/D ratio. This enables the pilot to get down into the field earlier, and leave more room for the later stages of landing.

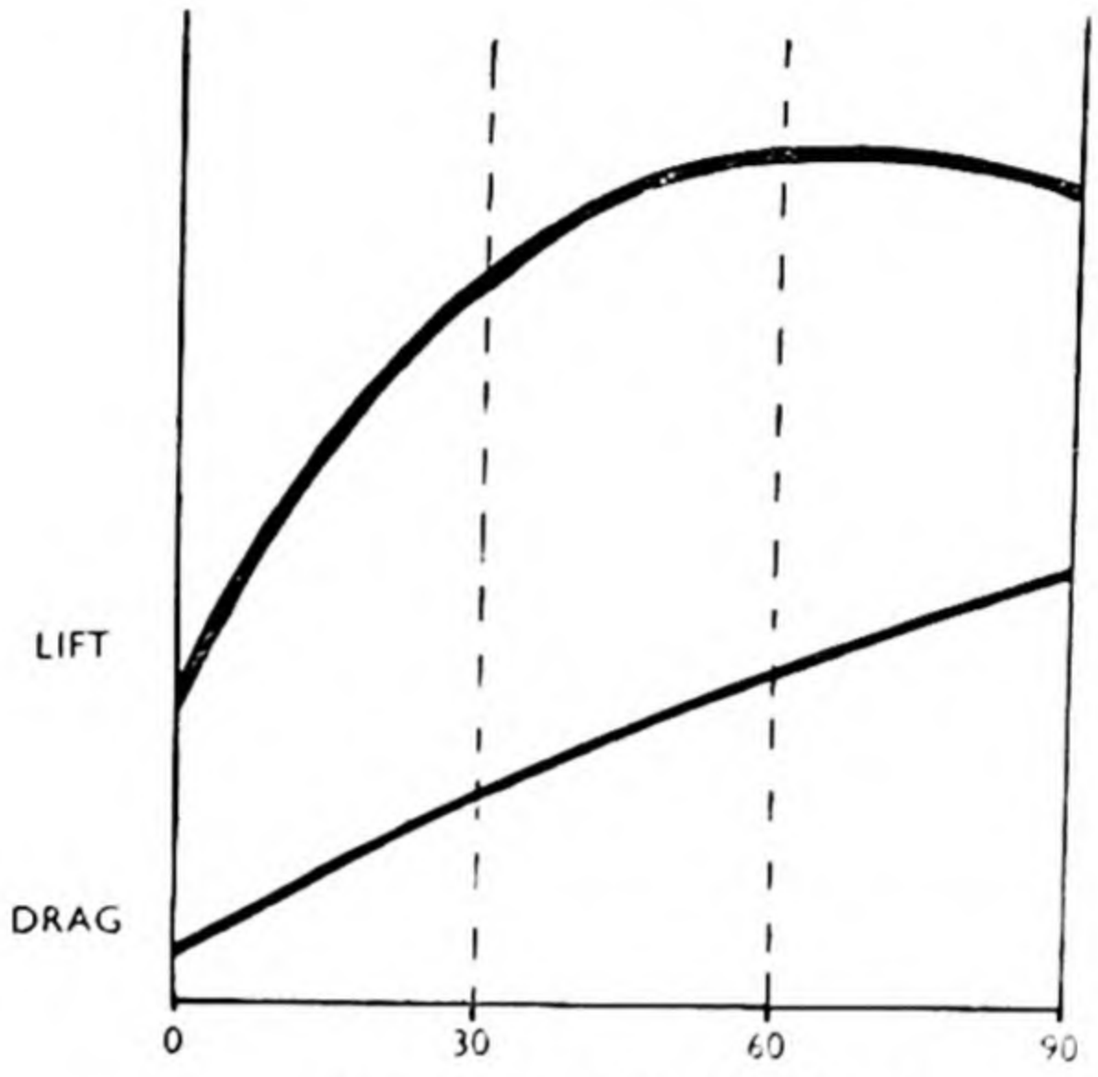


Fig. 43*a*.—Graph showing effect of a trailing-edge flap on the aerodynamic characteristics of the wing

(*b*) The hold-off is reduced because of the increased drag. During this part of the landing, the flaps are acting as an air-brake.

(*c*) The touch-down can be made at a lower airspeed, since the extra lift gives a lower landing speed to the aircraft.

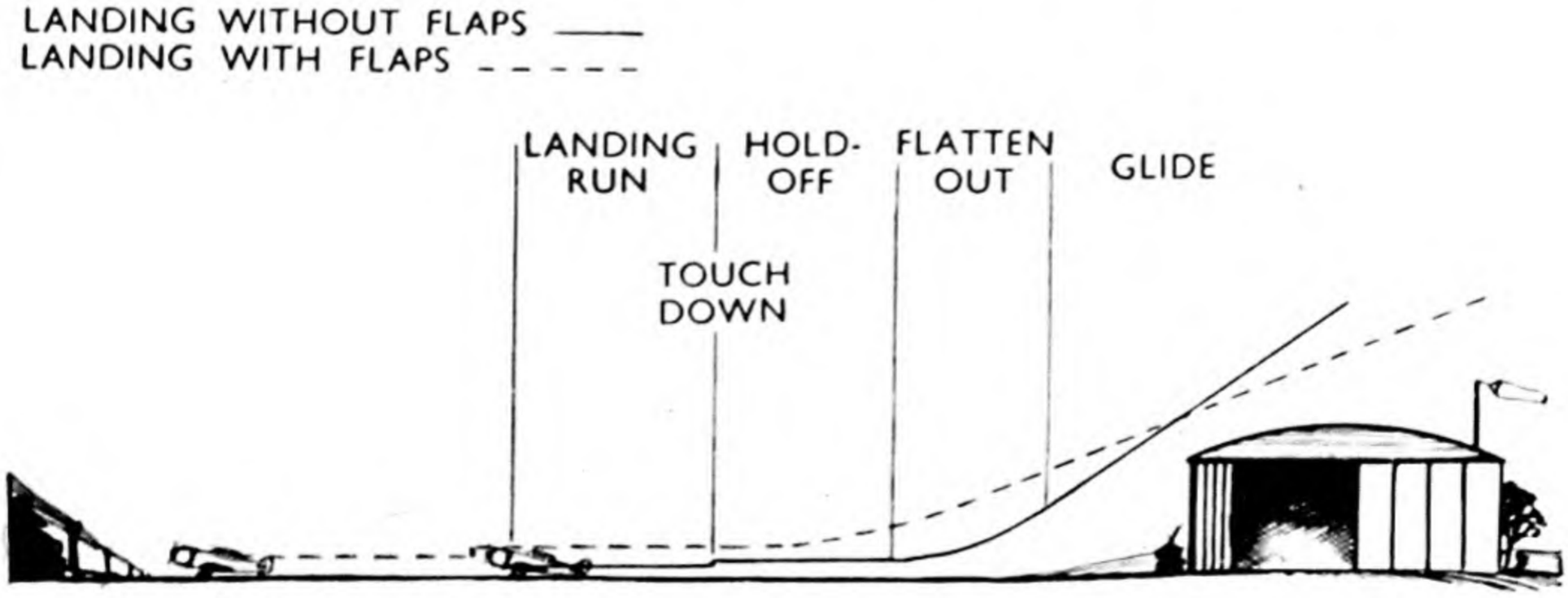


Fig. 44.—Effect of flaps on various stages of approach and landing

(*d*) The airbrake effect of the extra drag assists the wheel brakes in shortening the landing run. The flaps are most effective during the earlier part of the landing run before the aircraft is slowed down, whilst the wheel brakes may be applied more safely towards the end.

Since the lowest value of L/D and the highest value of L and D are required, the flaps are usually *fully down for landing*.

Use of Flaps in Take-off.

Here the problem is different, for what is required is the lowest possible airspeed at take-off, and the highest possible acceleration. Both these desirable qualities would shorten the take-off run, which is lengthening with every increase in wing-loading. Modern heavily laden bombers require specially built runways of great length.

The ordinary split flap a few degrees down will provide extra lift, which will reduce the speed at which the plane will become airborne, but the increased drag slows down the rate at which the aircraft gains speed, so that it is doubtful whether the take-off speed will be attained with any shortening of the take-off run. Certain types of flap, however, are specially designed to give lift. Such types shorten the take-off run of aircraft when heavily loaded.

Thus, if flaps are used at all *for take-off, they are only partly down.*

Use of Flaps in Manœuvres.

Flaps are used occasionally in manœuvres for two reasons. They may be used to provide drag to slow down the aircraft when it is about to make a turn, just as the brakes of a car are used when one wants to reduce speed before taking a sharp corner. They can be used to provide extra lift in order to reduce the minimum speed of flight, for it can be shown that the smallest radius of turn of an aircraft depends on the lowest speed at which it can fly. An aircraft with a high wing-loading, designed for high top speed, can be turned into an aircraft that can manœuvre more easily by the use of flaps. The Fowler flaps of the Lockheed Lightning are used for this purpose, as well as for landing (fig. 45).

A wing with the flaps down stalls at an angle of attack about a degree less than a wing without flaps or with flaps closed. This is quite different from a slotted wing, and one of the main advantages of the flap over the slot as a high-lift device is that it gives its extra lift at normal angles of attack, whilst the slotted wing must use abnormal angles to become effective.

This discussion on flaps should have succeeded in emphasizing one very important point, namely that the *minimum speed in flight depends on how much lift the wing gives*, and is not in any way affected by the drag, provided that the engine power is sufficient to overcome it.

Flaps generally give a decrease in stalling speed of between 10 to 15 miles per hour. The use of flaps allows the aircraft designer to build aircraft of higher wing-loadings than would otherwise be safe. Unless some improved form of flap is invented, or some other means

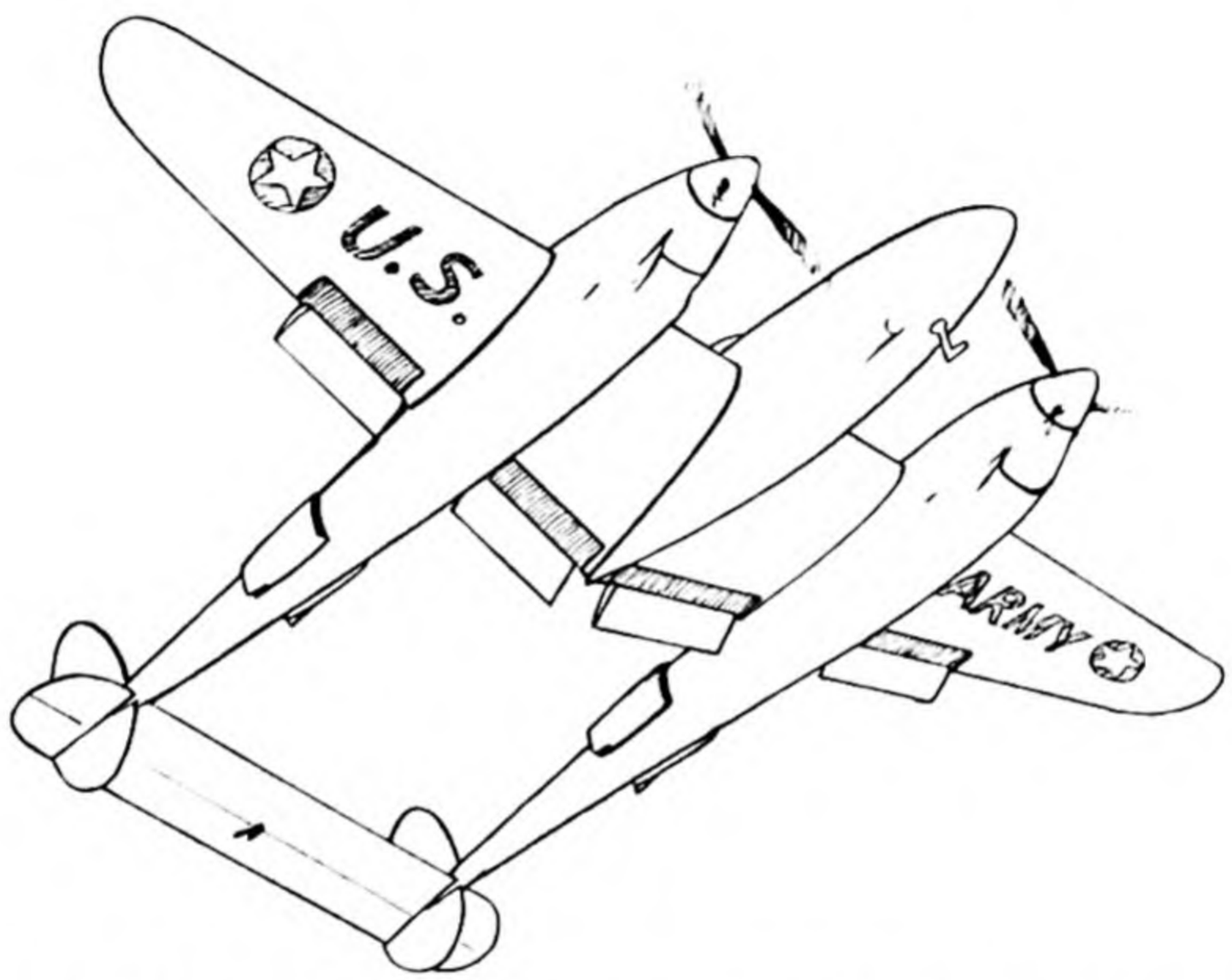


Fig. 45.—Lockheed (P 38) Lightning aircraft, showing modified Fowler-type flaps

of getting more lift from the wing for landing and take-off is discovered, wing-loadings at present are about as high as it is advisable to take them. Values of over 50 lb. per square foot are not uncommon, but landing an aircraft of this class at about 140 m.p.h. makes extravagant demands on a pilot's nerves, to say nothing of excessive tyre wear and the expense of long runways.

Various modifications of the present types of flaps are to be expected—flaps with leading-edge slots in front of them, ailerons that can be used as flaps, and so on, but none of these can effect any great change.

The telescopic wing has always sounded an attractive notion, but the weight and complication of such an arrangement, if it is to be sufficiently strong, make it impracticable.

In certain cases the real problem lies in take-off. Very long-distance aircraft would be so reduced in weight by the consumption of

fuel by the end of the journey that the wing-loading would be materially decreased; while, in wartime, the heavy bomber would be lighter by both the amount of its fuel consumed and by the considerable weight of its bombs on returning to land.

Special thought has been given, therefore, to the problem of take-off, within a reasonable distance, of heavily loaded aircraft.

In 1938 successful experiments were being made with the " Mayo " composite aircraft. A large flying-boat carried a small highly loaded float plane on its back. The combined wing-loading enabled the composite aircraft to take off, and, after height had been gained, the upper member (aptly named Mercury) was unlinked and proceeded on its own, with its mail, and a petrol load sufficient to give it an exceptional range.

Recently the idea of the " slip-wing " has been mooted. The idea here is to have attached temporarily above the aircraft an extra large wing, in the form of a simple lightly powered aircraft or glider. In this way the aircraft becomes for the time being very much like a biplane. After take-off the slip-wing is released and finds its way back to the airfield. Wing-loadings up to 100 and 200 lb. per square foot are confidently, perhaps too confidently, predicted for such aircraft.

Of course, the lowest landing speeds of all are to be found in the autogyro and helicopter aircraft.

Air Brakes (fig. 46).

Although there are times when it would be an advantage to have a flap that would increase lift without increasing drag, no flap so far designed will give this. There are times, however, when drag is wanted without lift, and this is comparatively easy to arrange.

Air brakes are really specially designed flaps, made strong enough to withstand the drag forces that they will encounter. They are useful in limiting the speed of the aircraft in steep dives. Sometimes they look like a split flap perforated with a large number of holes, but they may take other forms, and may be fitted on the upper or lower surfaces of the wings well forward near the leading edge.

Spoilers.

Spoilers are mainly used on gliders to decrease the L/D ratio of the wings, and steepen the gliding path during the approach to land. They usually consist of a long narrow surface on the top of the wing that can be turned up at right angles to the airflow when required.

Wheel Brakes and Tricycle Undercarriages.

The problem of flaps is to some extent allied to that of wheel brakes, in so far as both are used to shorten the landing run. As already mentioned, the flaps are most effective (and the safest) brakes while the airspeed is still high, but near the end of the landing run the wheel brakes come into their own.

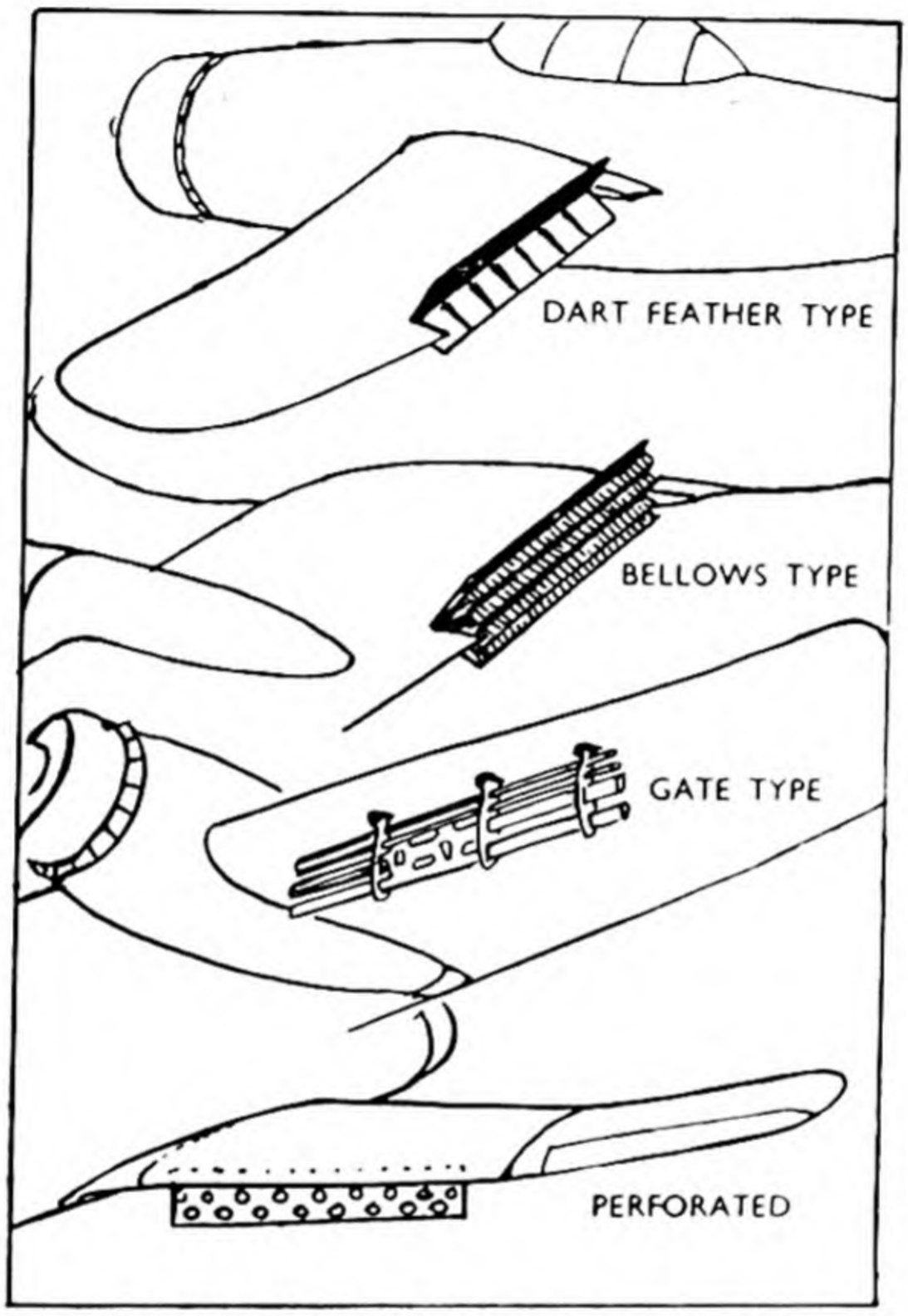


Fig. 46.—Some types of airbrake

In their turn wheel brakes are closely related to the type of undercarriage with which the aircraft is fitted.

The disadvantages of the more usual type of undercarriage are as follows:

(*a*) There is a tendency for the aircraft to pitch forward on to its nose if the brakes are applied too fiercely.
(*b*) There is a tendency for the aircraft to swing to one side when the brakes are applied.

The first tendency is due to the aircraft's centre of gravity, which lies well above the wheels, carrying on when the wheels are retarded by the brakes. The second tendency is due to the fact that the centre

of gravity lies behind the wheels, and if the aircraft swings slightly to one side, the inertia of the aircraft, acting from the centre of gravity, will cause the aircraft to swing still farther. It is somewhat as though a cyclist had applied the front brakes of his bicycle.

(*c*) There is a tendency with the conventional type of undercarriage for the aircraft to " bounce " if the touch-down is made at too high an airspeed. This is what will happen: because the speed of the aircraft is higher than the stalling speed, the attitude of the aircraft will be such as to cause the front two wheels to touch down first. The tail wheel will then come down and the increase in the angle of attack of the wings that results from this, together with the excess speed, will cause the aircraft to take off again.

The tricycle undercarriage overcomes these disadvantages and has other advantages to recommend it.

(*a*) The tendency to nose-over is prevented by the presence of the nose wheel (fig. 47).

(*b*) The centre of gravity of the aircraft is in front of the wheels to which the brakes are applied, and if the aircraft swings slightly to one side, the inertia of the aircraft, acting through the centre of gravity, tends to straighten out the plane again. This is like applying the back brake of a bicycle, and is illustrated in fig. 47.

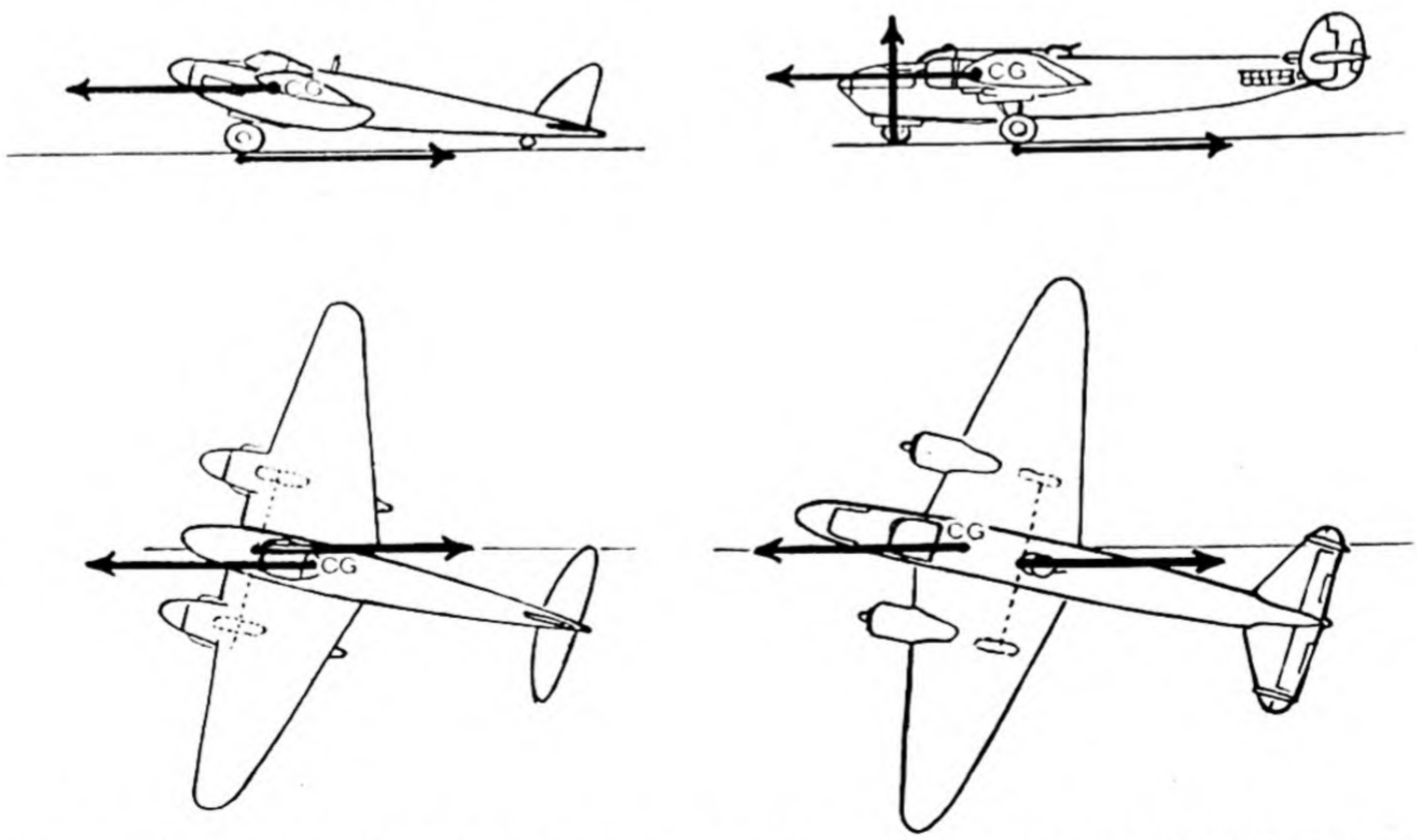


Fig. 47.—Showing how the tendency for an aircraft to " nose-over " or to swing during landing run is prevented by a tricycle undercarriage

(*c*) The tricycle undercarriage gives much better visibility during the landing and take-off runs.

(*d*) There is no tendency to " bounce " on landing, for if the aircraft lands so that the two main wheels touch down before the nose wheel, then the angle of attack of the wings will be decreased as the nose wheel comes down to the ground. This will give a sharp decrease in the lift from the wings and cause the aircraft to hold to the ground.

Some other points about the tricycle undercarriage might be mentioned. The brakes may be applied more fiercely because there is no danger of the aircraft pitching forward, and thus the landing run may be reduced.

A disadvantage may be discovered in the common failure of the nose wheel to stand up to the shock to which it is imposed during landing.

Finding the most suitable position for the centre of gravity relative to the two back wheels of the aircraft with the tricycle undercarriage is a matter of some difficulty. If it is too far forward, it is difficult to raise the nose during take-off; if it is too far back, there is a tendency for the nose of the aircraft to bounce up when taxying.

QUESTIONS

1. The pilot lowers the flaps of his aircraft before approaching to land. What is the effect of this on:

(*a*) The glide?
(*b*) The hold-off?
(*c*) The airspeed at touch-down?
(*d*) The landing run?

2. (*a*) Where are split flaps situated on the aircraft?

(*b*) What are the changes in lift, drag, lift-drag ratio, and position of the centre of pressure as the flap angle is changed (1) from 0° to 20°, and (2) from 60° to fully down?

3. (*a*) Explain briefly without a diagram how the fitting of a leading-edge slat to the wings of an aircraft enables more lift to be obtained from them.

(*b*) What are the disadvantages of the slat as a means of lowering the landing speed?

(*c*) What is the main purpose of wing-tip slats?

4. When the flaps are lowered for landing, the following factors affecting the wings are altered: lift, drag, the ratio lift/drag. Each of these affects some stage or stages of the approach and landing.

Rewrite the following table, completing it:

	Factor affected	Effect on this factor	Stage of landing or approach affected	In what way this stage is affected
(*a*)	Lift	.....	.....	.....
(*b*)	Drag	.....	.....	.....
(*c*)	*L*/*D*	.....	.....	.....

5. (*a*) What is a slat and what is a slot?

(*b*) What is the difference between fixed slots and automatic slots?

(*c*) What is the essential difference between slots and flaps in their action as high-lift devices?

(*d*) Why are slats seldom fitted to high-speed aircraft?

6. (*a*) What, in one word each, is the effect on the following of fully lowering the flaps: (1) lift, (2) drag, (3) lift/drag ratio?

(*b*) Why may a few degrees of flap shorten the take-off run if the flaps are Fowler flaps, and lengthen it if the flaps are split flaps?

(*c*) Why must flaps never be raised when flying near the ground?

CHAPTER VI

Stability

DEFINITION OF STABILITY. THE THREE AXES. LONGITUDINAL STABILITY. DIRECTIONAL STABILITY. LATERAL STABILITY. CONNEXION BETWEEN LATERAL STABILITY AND DIRECTIONAL STABILITY. SPIRAL INSTABILITY. THE MODERN METHOD OF TURNING. EFFECT OF FLAPS AND SLOTS ON STABILITY. STABILITY AT SLOW SPEEDS.

Definition of Stability.

Suppose an aircraft is flying at some safe height in undisturbed air, with the forces on the aircraft so balanced as to give equilibrium, and that, owing to some air disturbance, the nose of the aircraft drops. The pilot may bring the aeroplane back to its original attitude by using the controls, but let us see what might happen if he were to have his hands and feet away from the control column and rudder bar.

The nose of the aircraft might continue to drop, and the aircraft turn right over, or the nose might swing up and down whilst the aircraft followed an undulating path in which the amplitude of the oscillations grew gradually larger, until the aircraft stalled, or, once more, turned over. If the aircraft behaved in this fashion it would be *unstable*, and though, whilst flying level, it was in equilibrium, the condition of affairs would represent *unstable equilibrium.*

On the other hand, the aircraft might recover of its own accord, either directly or through a gradually diminishing oscillation. Such an aircraft would be *stable* in level flight, and the condition of flight would be one of *stable equilibrium.*

Stability may be defined as the ability of the aircraft to recover its previous condition of flight after some small disturbance, without the pilot's aid. The idea of stability defined in this way is quite a general one, and not confined to aircraft. Any body may be in equilibrium, that is to say, balanced under the action of the forces acting on it, but the equilibrium may be stable, neutral, or unstable. A conical shape, balanced on its base (fig. 48), is in stable equilibrium, for if it is tipped slightly to one side it will recover its previous position without external aid. The same cone, balanced on its point, is in unstable equilibrium, for the slightest disturbance causes it to topple right over; it does not recover of its own accord. If the cone is laid down

on its curved surface, the intermediate case of neutral equilibrium may be observed.

It is necessary in any condition of steady flight that the aircraft should not only be in equilibrium, but that this equilibrium should be stable. Otherwise, the pilot must continuously correct through the medium of his controls for those small disturbances inseparable from flying in the air, and the concentration that this would require would make flying very tiring.

It must not be thought that because an aircraft is unstable that it is necessarily unsafe to fly. It may have ample control and its movements may be slow enough to give the pilot ample time to correct

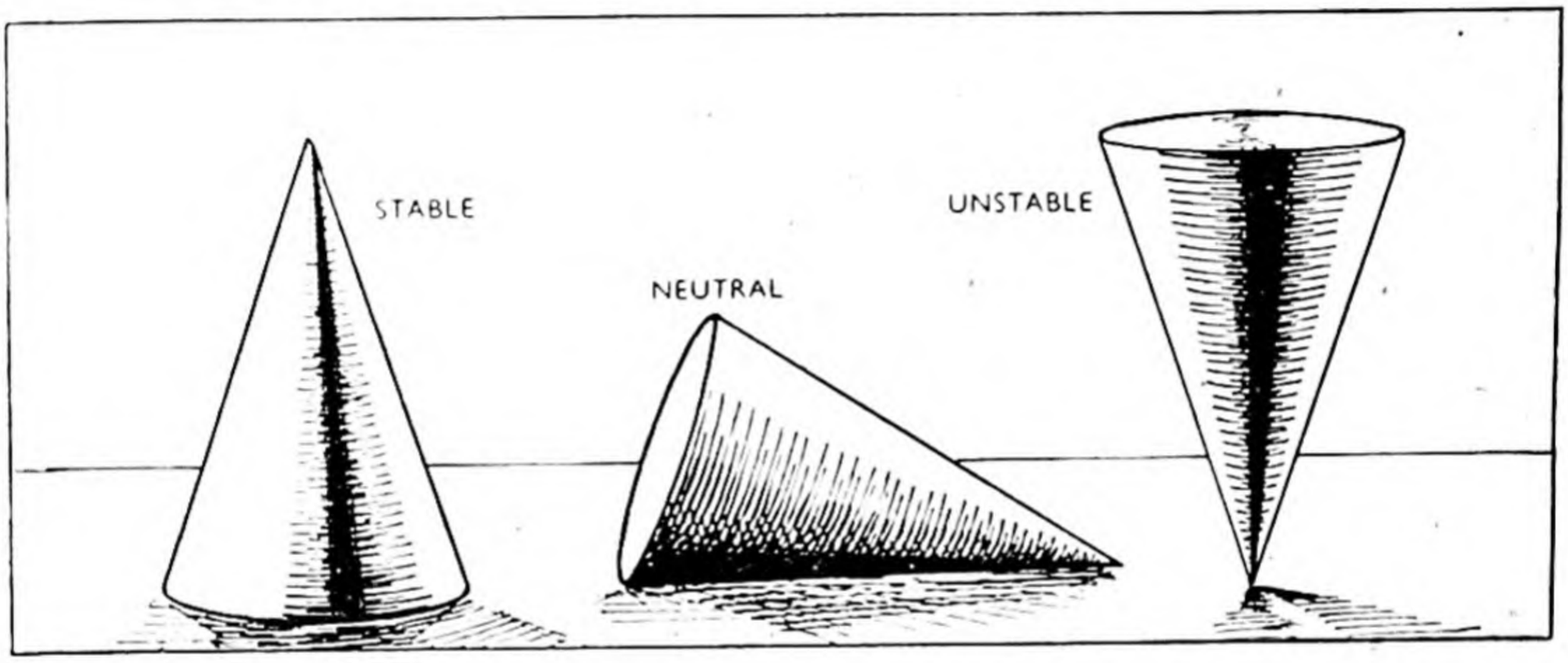


Fig. 48.—Stable, neutral and unstable equilibrium

them. The original Wright aircraft possessed no stability whatever, but numbers of people flew it quite successfully. However, although at one time it was thought that in order to attain sufficient manœuvrability a fighter aircraft should be unstable, it is now agreed that all aircraft should have some degree of stability.

The degree of stability needed varies, for a high degree of stability is not always compatible with manœuvrability and lightness of the controls. A long-distance transport plane should be designed to be very stable, so that it will hold to its course for long distances with the minimum of attention from the pilot.

The Three Axes (fig. 49).

The study of stability, and later of control, is complicated by the very involved movements which may be experienced. The only simple way is to consider each of the main types of movement separately, for the most complicated movement of an aircraft can be analysed into the movement of the centre of gravity in a straight line,

together with rotation about the three mutually perpendicular axes running through the centre of gravity. These axes are:

1. *The Lateral Axis*—a straight line which runs through the centre of gravity parallel to a line joining the wing-tips.
2. *The Longitudinal Axis*—a straight line that runs fore and aft through the centre of gravity in the plane of symmetry of the aircraft.
3. *The Normal Axis*—a straight line running through the centre of gravity at right angles to the other two axes. This axis will be vertical in level flight.

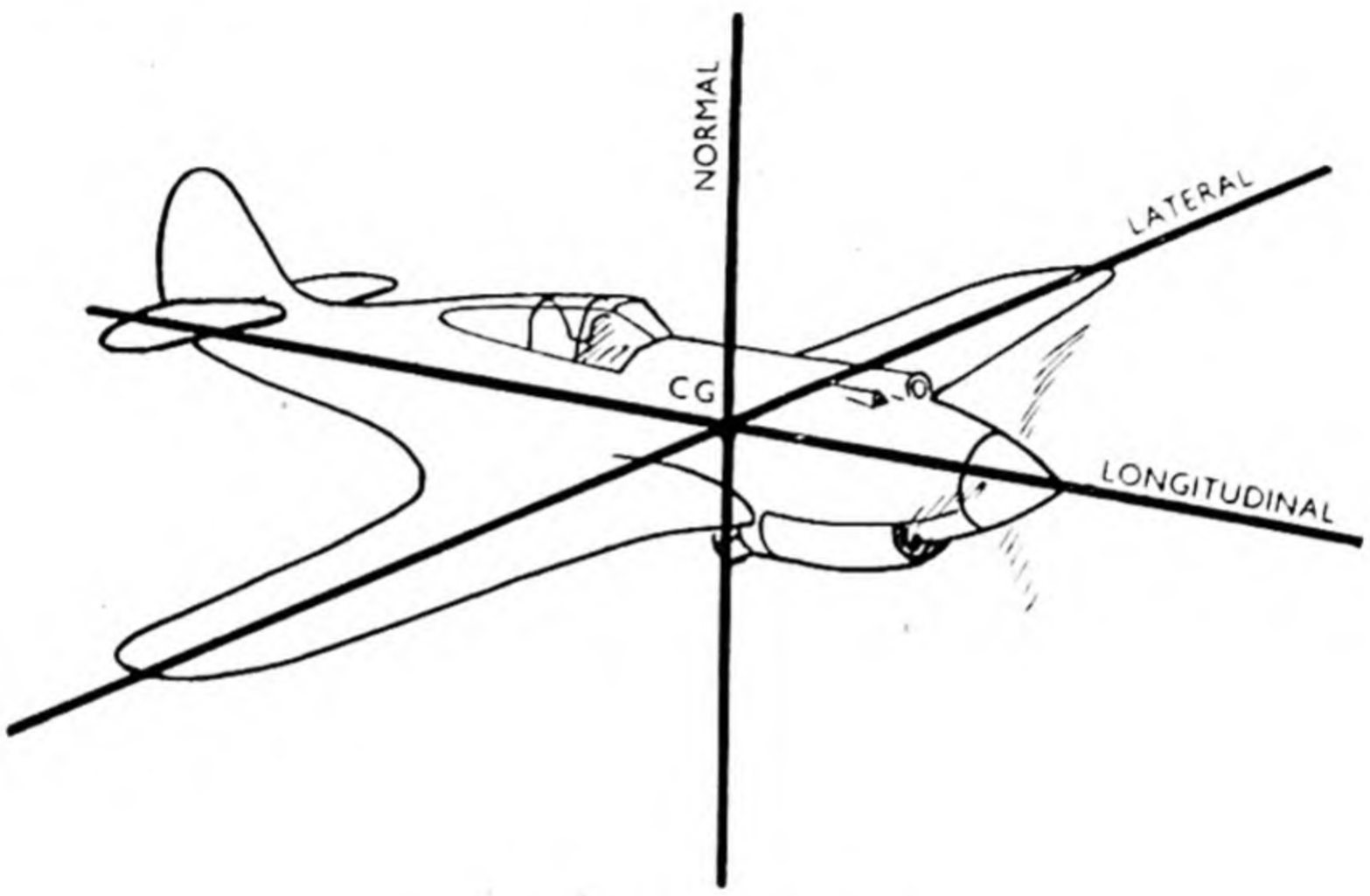


Fig. 49.—The three axes

Note that these axes are fixed relative to the aircraft, and not relative to the ground. If the nose of the aircraft drops, then the normal axis is no longer vertical, nor the longitudinal axis horizontal.

Longitudinal Stability.

Motion that takes place *round the lateral axis* is called *pitching* or looping. The plane in which the motion occurs, which is at right angles to the lateral axis, is called the *pitching plane* (fig. 50). If the aircraft moves in this way, the nose rises or falls and the longitudinal axis is tipped up or down. The ability of the aircraft to recover from a disturbance about the lateral axis is therefore called *longitudinal stability*, or stability in pitch.

Longitudinal stability is ensured by the tailplane and elevator. The tailplane is a fixed aerofoil parallel to the wings at the rear of the aircraft. In America it is called the stabilizer. The elevator is the

surface which is hinged at the trailing edge of the tailplane. As far as stability is concerned, they form one airfoil.

Without this surface the aircraft would be unstable in pitch because of the movement of the centre of pressure of the mainplane. This is what would happen if there were no tailplane and elevator. Suppose the aircraft to be flying level in equilibrium, and for the

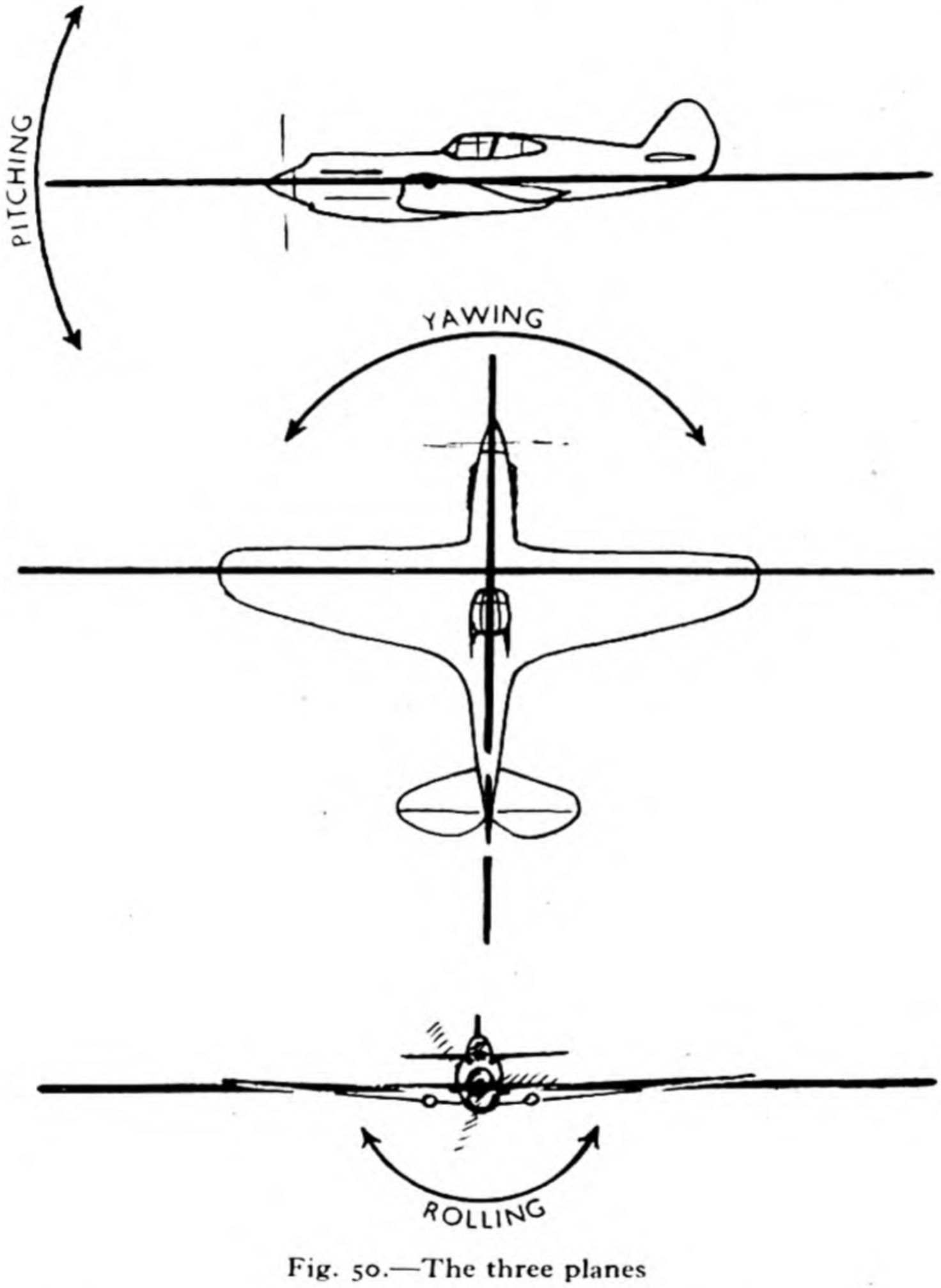


Fig. 50.—The three planes

sake of simplicity, let the lift and weight be acting along one line. If the nose of the aircraft were to rise, the centre of pressure would move forward towards the leading edge of the wings, and this would immediately introduce, through the lift and weight forces, a twisting effect or moment about the centre of gravity, tending to lift the nose of the aircraft still farther. If the nose of the aircraft were to drop, the centre of pressure would move towards the trailing edge of the wings, and once again there would be a twisting effect, tending to increase the extent of the disturbance by depressing the nose of the

aircraft still farther. It is clear that, as far as the wings alone are concerned, the aircraft is unstable. Reference to fig. 51 should make this clear.

Now what is the effect of the tailplane and elevator under these circumstances? One must remember that, owing to the inertia of the aircraft, when the nose rises the aircraft will not immediately start

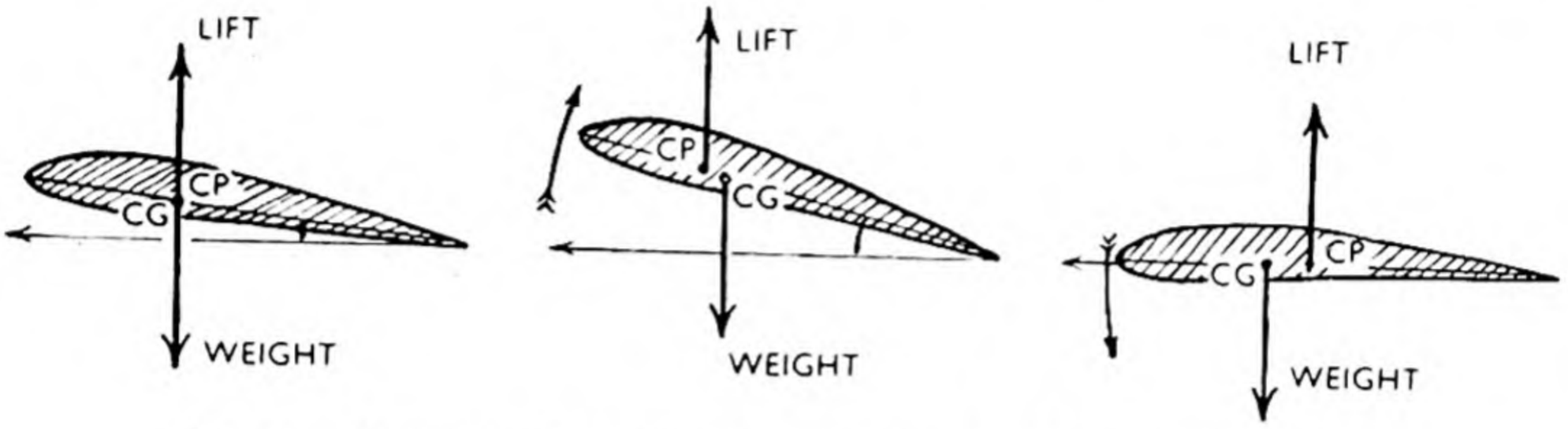


Fig. 51.—Movement of centre of pressure of the wing promotes instability

to climb, but for a short time the centre of gravity will continue to move along the same horizontal line as before. One can see that, owing to the attitude of the aircraft, the tailplane and elevator are for the time being striking the air at an increased angle of attack. If there were no reaction from them before, there is now an upward reaction, which gives a turning effect about the centre of gravity. This reaction, which, owing to the length of the fuselage, possesses considerable leverage about the centre of gravity, will overcome any

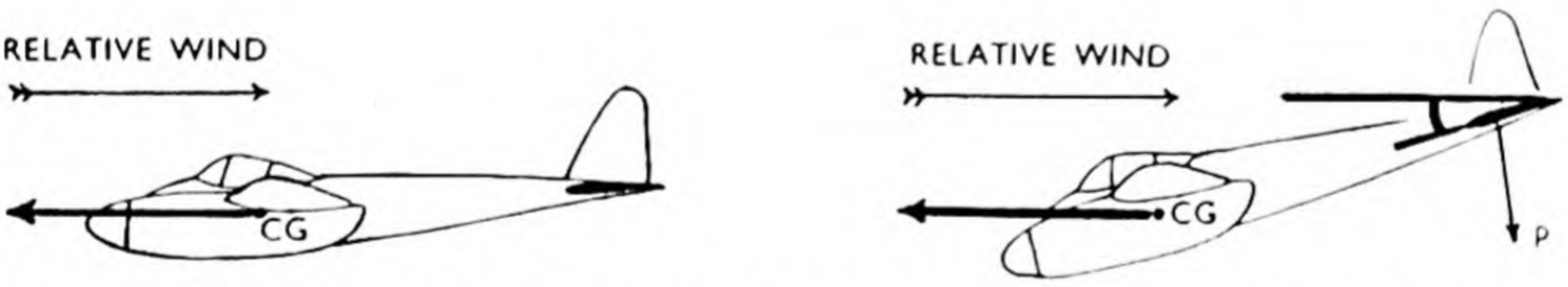


Fig. 52.—Diagram showing how longitudinal stability is achieved by the use of the tailplane and elevator surfaces

tendency to instability in the mainplane and enable the aircraft to recover automatically. If the nose of the aircraft drops, then a down-load on the tailplane and elevator appears, or if there were already a down-load, that down-load increases (fig. 52). Again, the aircraft will recover of its own accord.

An aircraft that possesses longitudinal stability will always try to turn into the line of flight. It is this that is mainly responsible for the nose of an aircraft dropping when the throttle is closed. For, as soon as the speed decreases, and the lift consequently becomes less than the weight, the aircraft begins to sink. Its line of flight is now inclined

to the horizontal, and the inclined airflow on the tailplane and elevator causes the aircraft to turn into the direction of this new relative wind. In other words, the tail lifts.

This is very useful, for, if the engine fails, the aircraft automatically assumes a gliding attitude at a time when the pilot has plenty to think about, and the danger of stalling is avoided.

Directional Stability.

If the aircraft turns *about the normal axis*, the motion is called " yawing ", and the plane at right angles to the normal axis, in which this motion occurs, is called the *yawing plane* (see fig. 50). The ability of the aircraft to recover from a yaw is called *directional or weather-cock stability*; it is dependent mainly on the fin and rudder. The fin is a fixed surface that lies at right angles to the tailplane and elevator, and the rudder is the hinged surface behind it.

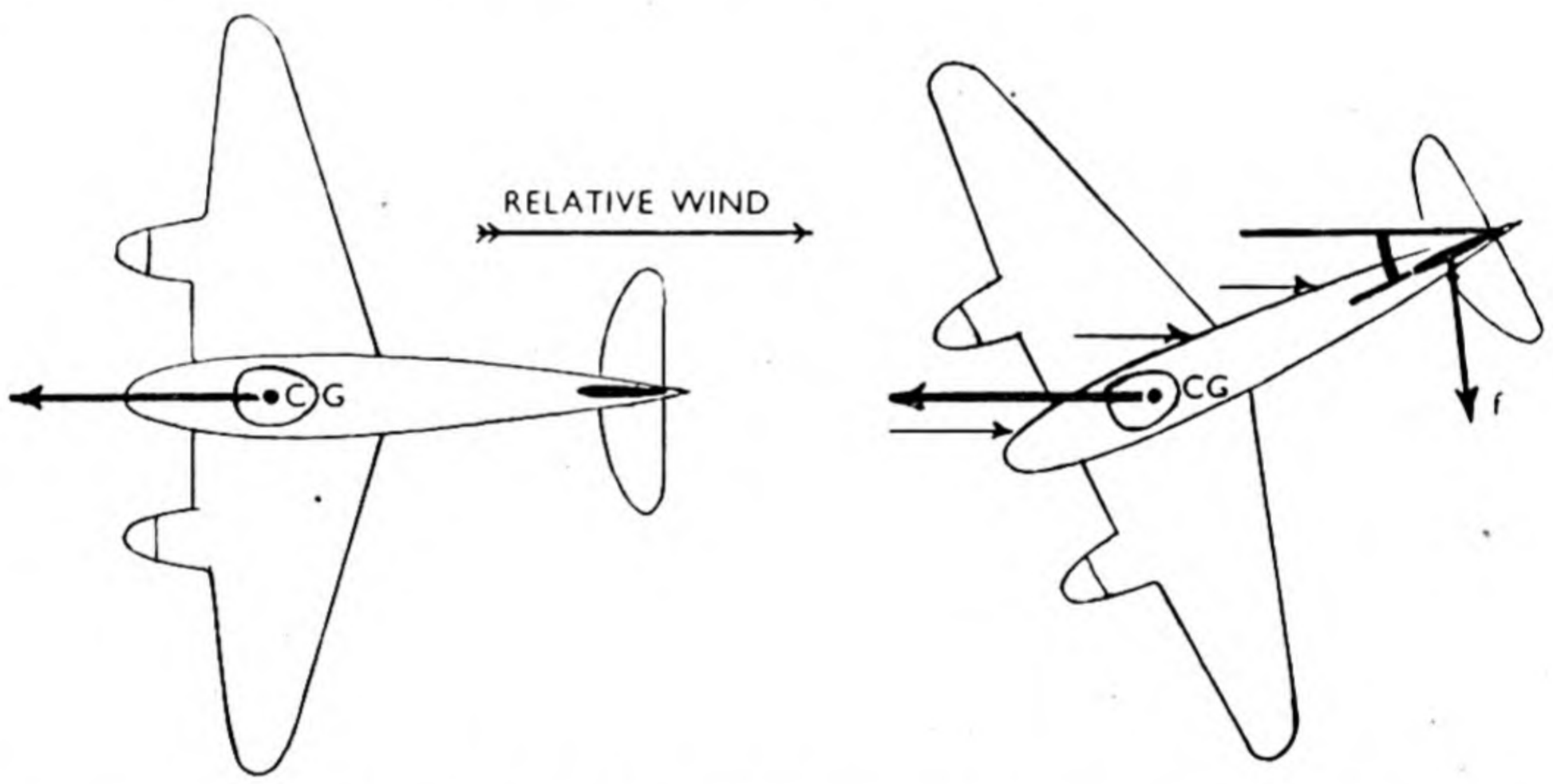


Fig. 53.—Diagram showing how the fin and rudder surfaces combine with the keel surface to give directional stability.

Again, the essential link in the argument is the effect of inertia in delaying the alteration of the flight path. If the aircraft is so disturbed that it points in a new direction, it will not immediately alter course, and the relative wind will strike it at an angle from the side. The effect of this on that part of the " keel surface " that is in front of the centre of gravity will be to create a twist that tends to increase the angle through which the aircraft was disturbed, whilst the effect on the part of the keel surface behind the centre of gravity will be opposite, and will tend to make the aircraft stable in the yawing plane. The fin and rudder will be at an angle of attack to the relative wind, and the reaction that results should be such as to give a final balance in the

favour of stability, so that the aircraft will turn into the relative wind and resume its previous attitude of flight without the pilot's aid. Fig. 53 shows the forces acting on the aircraft during the yaw.

The degree of stability, either longitudinal or directional, depends on the area of the stabilizing surface, its distance behind the centre of gravity (length of the fuselage), and the airspeed over it. The distribution of the keel surface in front of and behind the centre of gravity is another factor which contributes to the degree of directional stability. An aircraft with a short fuselage will generally need large tail surfaces. When an aircraft is moving slowly, directional and longitudinal stability will be decreased because of the slower airflow over the stabilizing surfaces. This is particularly noticeable with the fin and rudder when taxying.

Lateral Stability.

When an aircraft turns about the longitudinal axis, so that one wing lifts and the other drops, the motion is called *rolling*. The plane at right angles to the longitudinal axis, and parallel to the plane in which the propeller rotates, is called the rolling plane (fig. 50). When

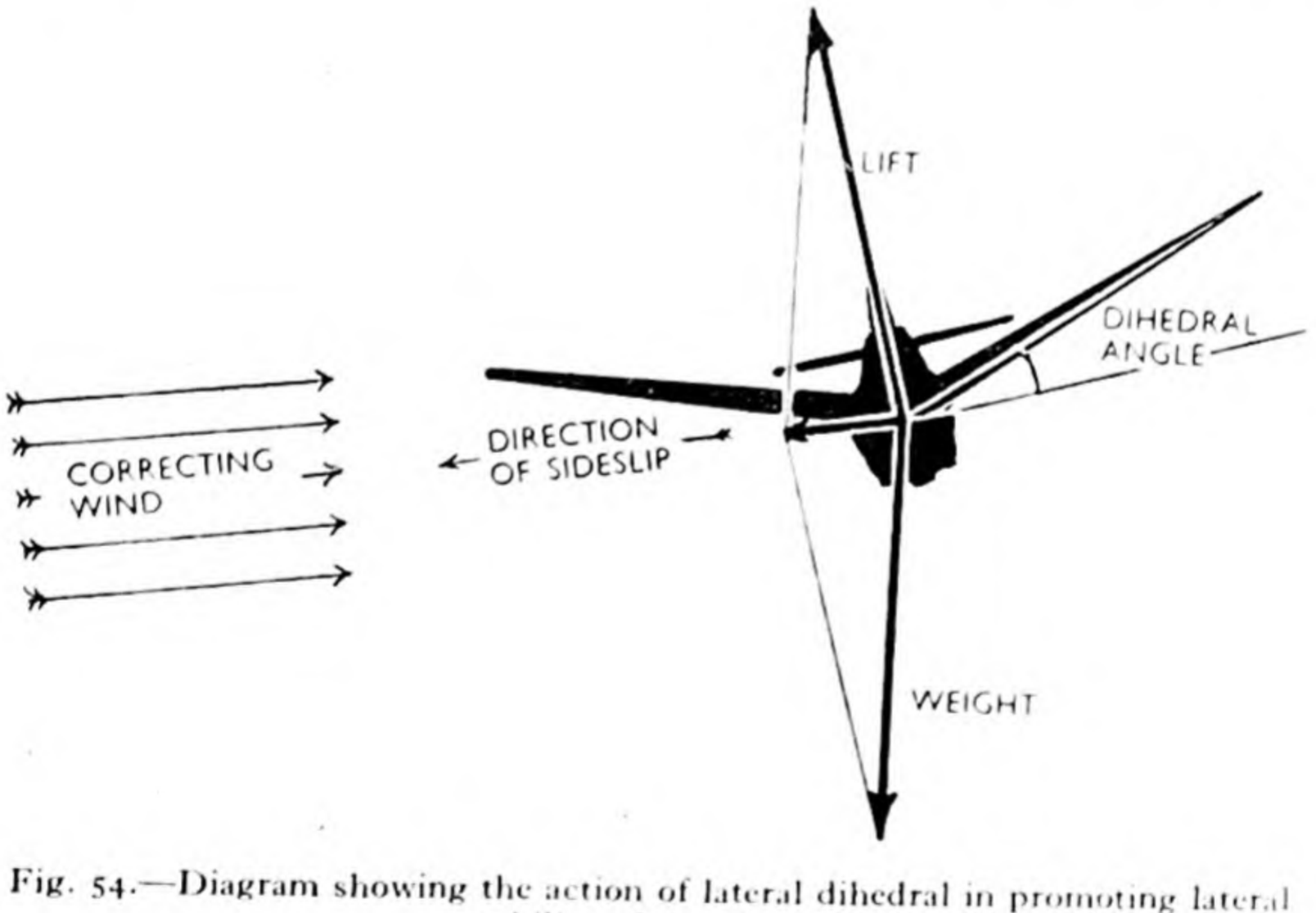


Fig. 54.—Diagram showing the action of lateral dihedral in promoting lateral stability of the aircraft

the aircraft is disturbed in the rolling plane, so long as the roll continues there will be a force tending to stop it that will result from the wings striking the air. This force will cease as soon as the motion ceases, and cannot therefore be instrumental in restoring the aircraft to an even keel. There are three ways of bringing into play restoring forces that will give the aircraft lateral stability, and the most effective

of these is by means of positive *lateral dihedral* of the wings. The wings, or part of the wings, are turned up at an angle to the lateral axis, and *the angle between the centre line, from wing root to wing-tip,*

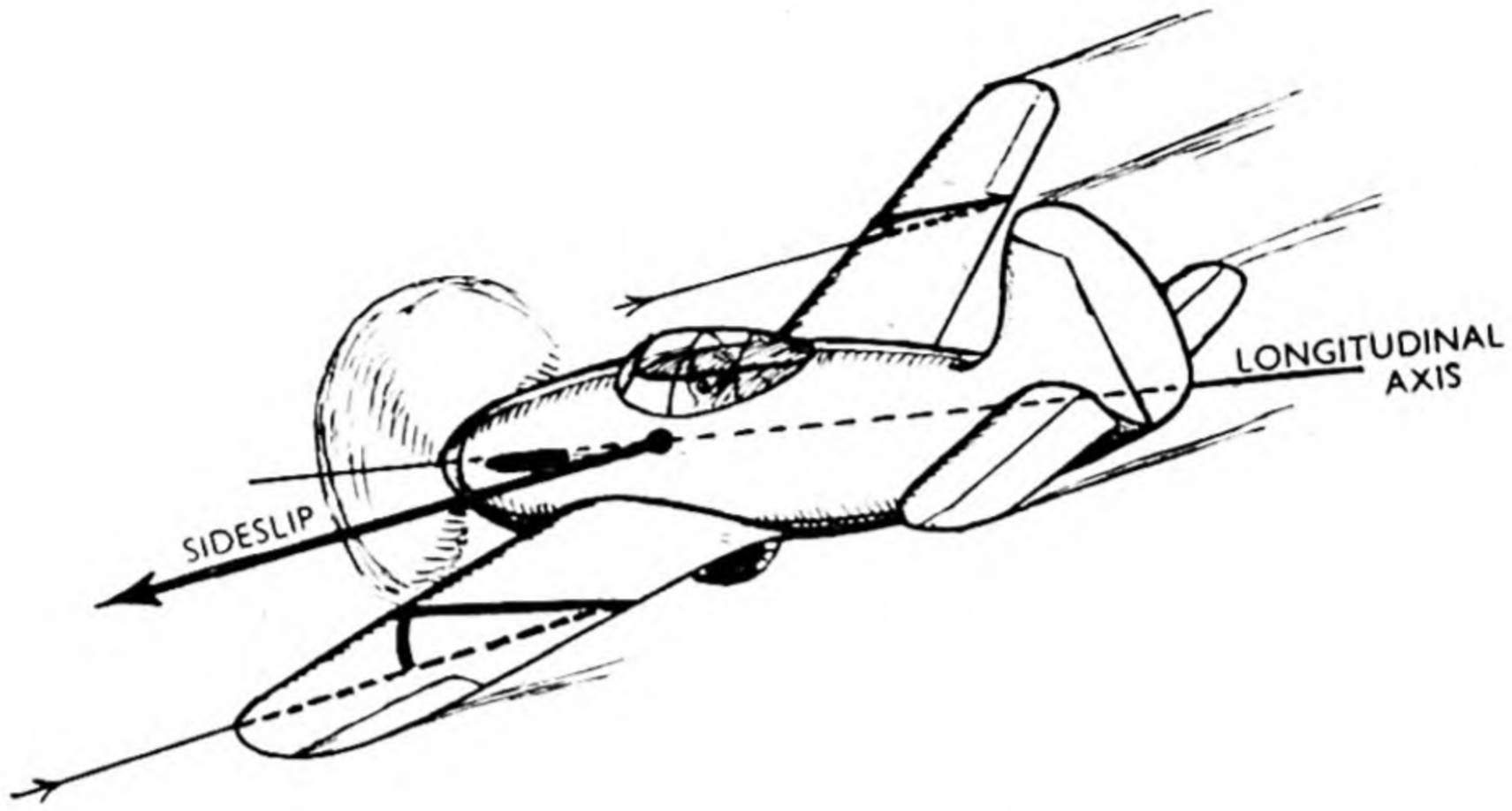


Fig. 55.—Diagram showing how, owing to lateral dihedral, the airflow strikes the two wings at different angles of attack during the sideslip that follows a roll

and the lateral axis is called the dihedral angle, in this case, positive dihedral, since the angle is on the side of the lateral axis opposite to the undercarriage.

When the aircraft is disturbed in the rolling plane, the lift from the wings is no longer vertical, and the resultant of this lift and the downward acting weight is a small force sideways that causes the aircraft to sideslip in the direction of the lower wing. This sideslip is an essential factor in the restoration of the aircraft to an even keel, for it brings into play

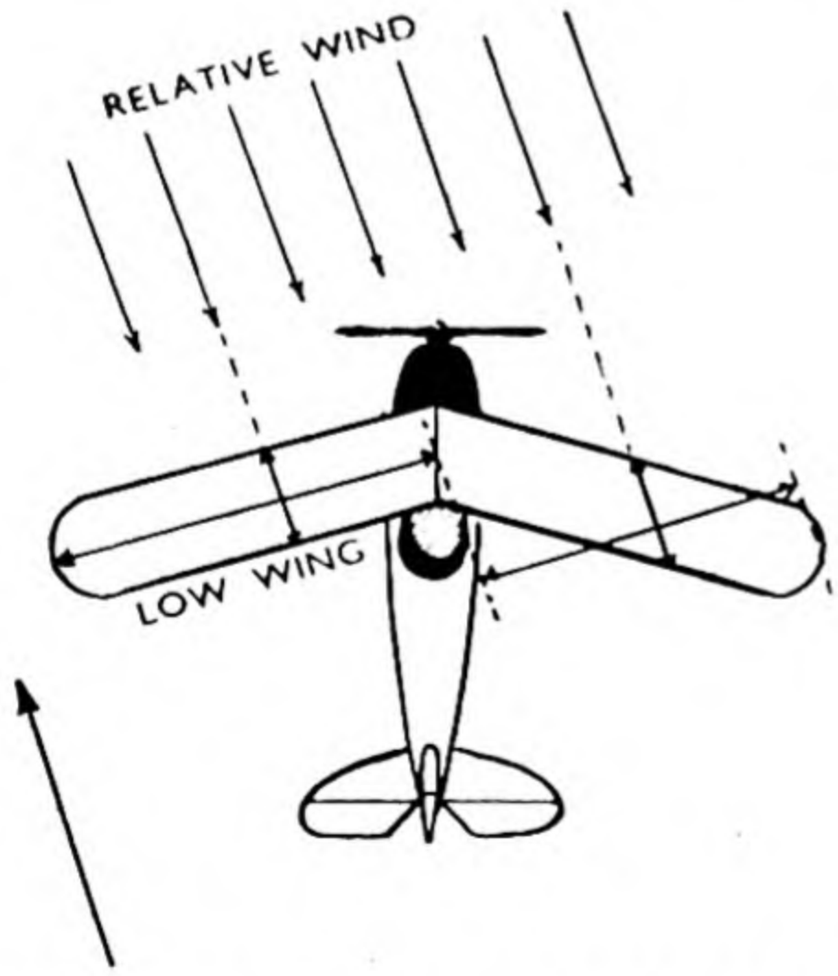


Fig. 56.—Sweepback and lateral stability

Fig. 57.—Effect of high wing and low C.G. on lateral stability

a new relative wind, opposite to the direction of the sideslip, as shown in fig. 54. The result of this correcting wind and the relative wind due to the forward motion of the aircraft is a wind striking the aircraft at an angle from the side. It can be shown that if there is

lateral dihedral to the wings, this relative wind will strike the lowered wing at a greater angle of attack than the raised wing, and the consequent difference in lift will restore the aircraft to its original state of level flight. An attempt to illustrate this is made in fig. 55.

Sweepback of the wings has some effect on lateral stability. Wings with sweepback are bent backwards towards the tail. Again the roll is followed by a sideslip and a diagonal relative wind. The result of this is an alteration in the effective aspect ratio of the two wings, as shown in fig. 56, and the lower wing becomes the more effective in giving lift. Thus, the aircraft is restored to an even keel.

High wings and low centre of gravity will give lateral stability without the use of dihedral. When the aircraft sideslips, the resulting side drag on the wings tends to hold back the aircraft at that point, whilst the inertia of the aircraft, acting through the centre of gravity, tends to carry on (fig. 57). This brings into play a restoring twist.

Connexion between Lateral Stability and Directional Stability.

If an aircraft yaws in flight, during the yaw one wing is travelling faster and will give more lift than the other. The aircraft will roll as a result of this unequal lift. *Thus, a yaw produces a roll.*

If, for any reason, the aircraft rolls, it will sideslip in the direction of the lower wing, and whilst this is happening, the airflow will meet it from the side. It has been explained how this tends to right the aircraft; not only will the airflow strike the wings, but also the keel surface. The aircraft will tend to turn into the airflow because of its directional stability. In other words, *a roll produces a yaw.*

It is very easy to see this with a slow-flying model aircraft. If some disturbance in the air causes one wing to drop, it recovers from the roll pointing in a different direction, a little off course, as a result of the yaw that accompanied the roll. Rolling and yawing are so closely connected that some writers treat them under one heading.

Spiral Instability.

If an aircraft is given too much directional stability and too little lateral stability, the results may be as follows.

If one wing drops, there will be the effect of the lateral dihedral tending to right the aircraft, and there will be the yaw that accompanies the roll. But the yaw itself, as we have seen, will produce a roll, and this tendency may overcome the attempt of the dihedral to bring the aircraft back to an even keel. If this is so, the roll will increase the yaw, and the yaw will increase the roll, and both bank and turn become greater and greater, until eventually the aircraft will go

into a spiral dive. This is called spiral instability, and is a result of too much directional stability relative to the amount of lateral stability. This state of affairs should never occur with well-designed aircraft.

The Modern Method of Turning.

Use is made in modern aircraft with a fairly high degree of directional stability of this interconnexion between roll and yaw. In Service types, the rudder is very little used in the air. When the pilot wishes to turn, the aircraft is banked: it starts to sideslip, and hence to yaw, and the aircraft begins to turn. The tendency for the nose to drop must, of course, be counteracted by the use of the flying controls. Some pilots will not agree that the aircraft sideslips, but without sideslip, however small it may be, at the start, the aircraft would not begin to turn.

This method of turning is not very effective on elementary training types with less directional stability, and with them correct co-ordination of rudder and ailerons is essential.

Effect of Flaps and Slots on Stability. Stability at Slow Speeds.

Flaps have little effect on stability, except that some of the more powerful types, such as the Fowler and Gouge flaps, move the centre of pressure back to such an extent that there is definite increase in the nose-over tendency. This, however, is an alteration of equilibrium rather than of stability.

When slots are used to increase stability at slow speeds, they are confined as a rule to the wing-tips. Suppose that an aircraft is flying near its stalling speed, so that the nose is high and the wings are striking the air almost at stalling angle. If the aircraft is disturbed in any way in the rolling plane, it can be shown that the angle of attack of the dropping wing is increased and that of the rising wing decreased. (This is due to an additional upward component to the airflow striking the dropping wing, whilst on the other wing the additional airflow is downwards.) There is therefore a real danger that the dropping wing may stall. If it does so, the resulting loss in lift will cause the wing to drop still farther. The continued roll will maintain the dropping wing in the stalled condition and there will be no lateral stability. The aircraft will turn over. This is called *autorotation*. It is the start of the spin. Postponing the stalling angle by the use of the wing-tip slots largely eliminates this danger.

Autorotation may result from an attempt to use the ailerons when the aircraft is flying slowly, and this will be mentioned when control is discussed.

QUESTIONS

1. An aircraft with lateral dihedral is in steady horizontal flight when a sudden gust of wind causes the starboard wing to drop. Describe and account for the subsequent behaviour of the aircraft until it is again on an even keel.

2. (*a*) When an aircraft is said to be stable in flight, what does this mean?

(*b*) Explain how weathercock stability (stability in yaw) is obtained in the air, and how it operates.

3. (*a*) Enumerate but do not describe three methods of achieving lateral stability.

(*b*) On what factors does the stability in pitch of an aircraft depend?

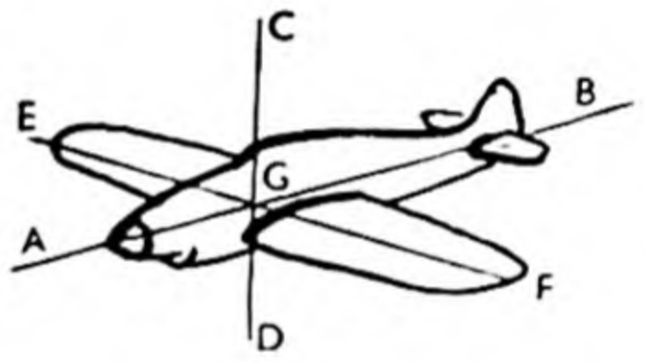
(*c*) Explain why the wing alone tends to make the aircraft unstable in pitch.

4. (*a*) An aircraft flying straight and level is disturbed so that it yaws to the starboard. Explain how it will bring itself back to the original course.

(*b*) What secondary effect on the aircraft would result from this yaw? Why?

5. In the diagram:

(*a*) Which plane contains ABCDG?
(*b*) Which plane contains ABEFG?
(*c*) About what axis by name does motion in the plane ABEFG take place?
(*d*) What is the name of the axis AG?
(*e*) What motion occurs if the point A moves towards the present position of E?
(*f*) What motion occurs if the point B moves towards the present position of C?
(*g*) What movement of what control surface would cause this movement referred to in *f*?



6. (*a*) An aircraft is flying level very near its stalling speed, when a gust of wind causes the port wing to drop. Explain the movement of the aircraft that will probably result from this.

(*b*) What is this movement called?
(*c*) What is the further consequence of this movement?
(*d*) What is the condition of the wings during this final stage?

7. (*a*) Rewrite and complete the following sentences:

1. ..... stability by means of dihedral assists recovery from .....
2. ..... stability by means of keel surface with fin and rudder assists recovery from .....
3. ..... stability by means of ..... assists in recovery from pitching.

(*b*) Explain with the aid of diagrams how the third of these works.

CHAPTER VII

Control

DEFINITION OF CONTROL. LONGITUDINAL CONTROL. LATERAL CONTROL. DIRECTIONAL CONTROL. EFFECTIVENESS OF THE CONTROLS. AILERON DRAG. AERODYNAMIC BALANCE. TRIMMING DEVICES. MASS BALANCE AND FLUTTER. FLIGHT AT SLOW SPEEDS. SPIN.

Definition of Control.

However stable an aeroplane may be, the pilot must have power to control it. *By control is meant the power to turn an aircraft about any or all of its three axes.* Control and stability are not by any means the same thing. In fact they may oppose each other, for an aircraft that is very stable will always try to return to its original line of flight: in other words, it will oppose the pilot's attempts to manœuvre it.

In early glider experiments carried out by such pioneers as Lilienthal or Pilcher, the glider itself was fitted with no control whatsoever, but the pilot was able, from his suspended position in the machine, to control its movements by swinging his body. Other early experimenters arranged for control in the yawing and pitching planes, and considered it unnecessary to provide means whereby the aircraft could be made to roll or bank. The Wright Brothers were the first to realize that three controls, rudder, elevator, and ailerons were necessary. The position of the rudder and elevator has already been explained; the ailerons are hinged portions of the wings at the trailing edge near the wing-tips.

Longitudinal Control.

When the aircraft is made to pitch so that the nose rises or falls, longitudinal control is being exercised. The movement takes place in the pitching plane, and about the lateral axis. The elevator which provides this movement is connected to the pilot's control column in the cockpit, and the control is said to be instinctive, because when the control column is pushed forward, the nose of the aeroplane drops. What happens when the pilot pushes the stick forward in this way is that the elevator is depressed. This virtually increases the camber of the airfoil formed by the tailplane and elevator. In this way the upward reaction is increased, or the downward reaction reduced, and

the change of moment or twisting effect about the centre of gravity of the aircraft causes the nose to drop. The connexion between the control column and the elevator in light aircraft is by means of wires, but in larger and more advanced types the linkage may be through push rods, chains and pulleys, or by hydraulic mechanism, and this gives a more positive form of control, freer from the backlash associated with slack control wires.

Lateral Control.

Here the movement is called rolling or banking; it occurs in the rolling plane and takes place about the longitudinal axis. It is provided by the ailerons, which are so connected to the control column that when it is moved to the left, the port aileron is elevated and the starboard aileron depressed. The effect of the depressed aileron is to increase the effective camber of that portion of the wing to which it is attached and so increase the lift on that side. The effect on the other wing is just the opposite. The resulting difference in lift between the two wings causes the aircraft to bank in such a way that the starboard wing goes up and the port wing goes down. Since the aircraft turns the same way as the control column, the movement is again instinctive. Sometimes, instead of the stick moving from right to left, or vice versa, a wheel at the head of the control column is used; it turns the same way as the aircraft.

Directional Control.

This describes control in the yawing plane, about the normal axis, and is brought about by the movement of the rudder. The rudder is connected to the rudder bar at the pilot's feet. If the pilot pushes the left side of the rudder bar forward with his left foot (the movement is normally very slight), then the rudder moves to the left or port side and produces with the fin a cambered airfoil giving a reaction to the right, and tending to turn the aircraft nose to the left about the centre of gravity. A pilot finds the movement becomes automatic, or " instinctive ", but it is exactly opposite to what happens on a bicycle when the handle bars are moved the same way as the rudder bar.

Thus, the primary effects of the control can be stated:

1. The elevator controls the aircraft in the pitching plane.
2. The ailerons control the aircraft in the rolling plane.
3. The rudder controls the aircraft in the yawing plane.

In a steep bank it is the rudder that holds the nose of the aircraft on the horizon, and the elevator that controls the rate of turn. This is an apparent reversal of the use of these two controls, and it might be supposed that this would be confusing to the pilot. But the elevator still controls the aircraft in the pitching plane, and the rudder stills controls it in the yawing plane, and so the pilot finds no difficulty in using them.

Effectiveness of the Controls.

This will depend on their area, their distance from the centre of gravity of the aircraft, and the speed of the airflow over them. If, for instance, the fuselage of the aircraft is short, the leverage that the rudder and elevator possess about the centre of gravity will be small, and it is to be expected that the surfaces will make up in area what is lost in leverage. The area of the keel surface in front of the centre of gravity must also be considered, just as in stability when the effectiveness of the rudder is thought of, but in this case, a large keel surface in front of the centre of gravity will help the rudder to produce the yaw.

At high speeds, when the airflow over the control surfaces is fast, the reaction that they obtain for a given deflection will be greater, just as is that of the wing itself. At a slow speed the surfaces are less sensitive. This makes a difference to the feel of the controls: at high speeds the controls may feel stiffer and heavier. On the ground the ailerons are ineffective as ailerons, whilst the movement of the rudder that is required to turn the aircraft whilst taxying is very coarse. The order in which the controls become effective in take-off is first, rudder; second, elevator; lastly, ailerons. The order in which they lose their effectiveness in landing is the reverse of this.

When the throttle is opened on the ground, the slipstream over the tail surfaces makes them more effective, but, of course, does not influence the ailerons.

Aileron Drag.

Unfortunately, when the pilot uses the ailerons, there is a tendency for the downgoing aileron to increase the drag on that side, whilst on the other side a decrease results from the upturned aileron. This is especially so at slow speeds, when the wings are at high angle of attack, and it tends to make the aircraft yaw in the direction of the downgoing aileron. The effect is called aileron yaw.

Two ways of overcoming, partially at any rate, this result of aileron drag are in common use. They are:

1. *Frise Ailerons* (fig. 58), which are so shaped and hinged that when the aileron is raised its leading edge projects into the airflow below the wing, increasing the drag on that side, and so compensating for the increase on the other side due to the lowered aileron.

Fig. 58.—Frise ailerons

2. *Differential Ailerons* (fig. 59). In this case the drag on the two sides is made more nearly equal by arranging that the raised aileron shall turn through a larger angle than the lowered one.

Fig. 59.—Differential ailerons

By the use of either one or both of these methods aileron yaw has been reduced to a minimum in modern aircraft, and the pilot has seldom to worry much about it nowadays. It is noticeable on monoplanes of large wing span, when, at the very beginning of a turn, aileron drag causes a momentary yaw in the wrong direction.

Aerodynamic Balance.

When the pilot deflects the controls, the reaction of the airflow tries to return them to the neutral position. The pilot is pushing the control against this force, and although the effort required may not be very large at low speeds or with small aircraft, with large aircraft or at high speeds it would make control difficult. There are three ways at present in use by means of which the controls are made easier to turn.

The *horn balance* is illustrated in fig. 60. The pressure of the airflow on the " horn ", that part of the control surface in front of the hinge, pushes the surface in the same sense as the pilot is attempting to turn it, and diminishes the effort that he must apply. A more adequate explanation can be put forward in terms of the alteration in the position of the centre of pressure, for, with the horn balance, the point from which the reaction acts is nearer the hinge, and the restoring moment that it exerts about the hinge, and against which the pilot is working, is therefore diminished.

The *inset hinge* (fig. 60) is merely a variation of the horn balance, but in this case the surface in front of the hinge is broken up into several parts.

The *balance tab* is perhaps the neatest way of reducing the effort needed to turn a control surface. The balance tab is a small hinged airfoil which forms part of the trailing edge of the control surface itself. The balance tab is linked to the main control surface in such a way that, when the control surface is deflected in one direction, the tab is deflected in the other. Fig. 60 shows how this is brought about.

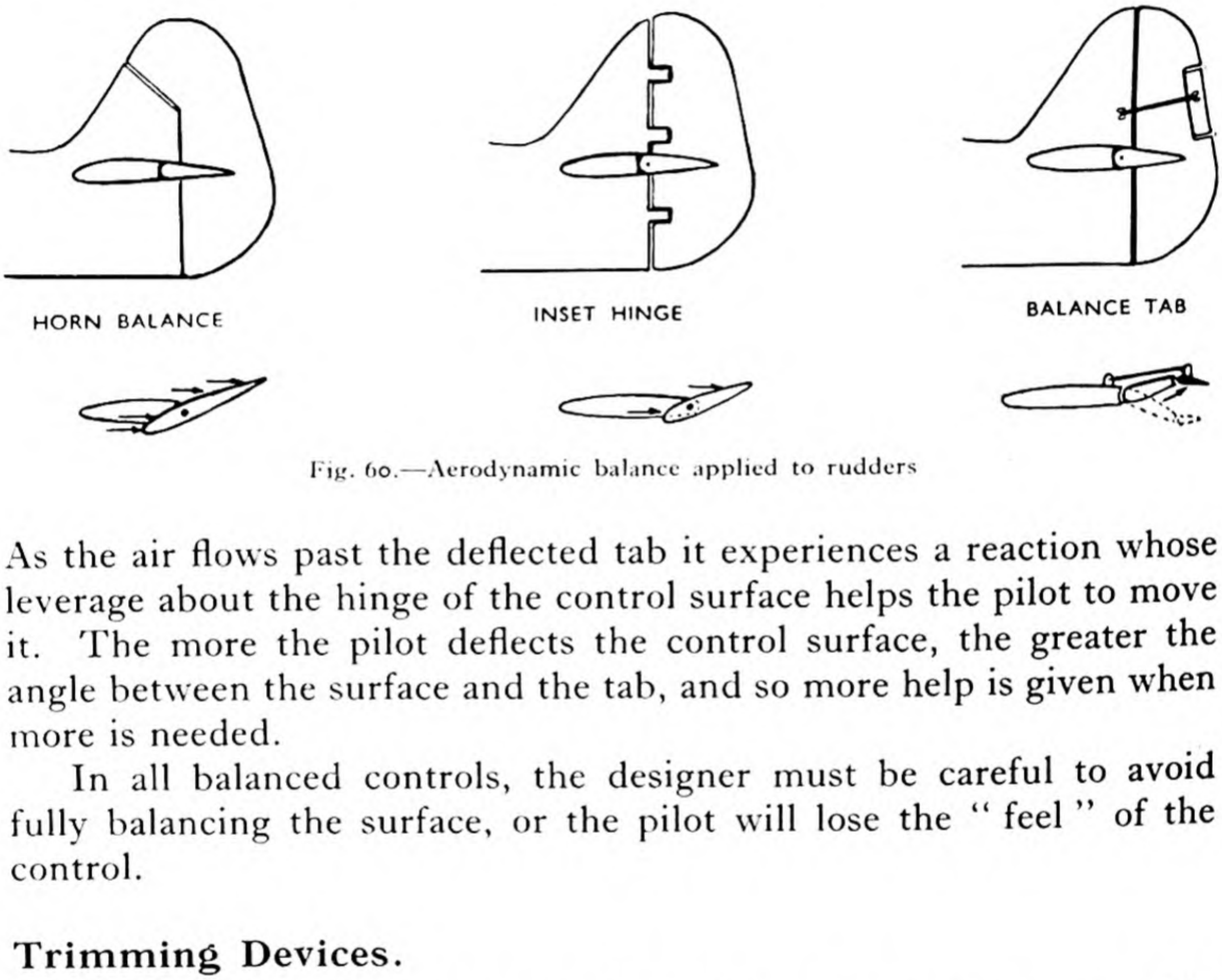


Fig. 60.—Aerodynamic balance applied to rudders

As the air flows past the deflected tab it experiences a reaction whose leverage about the hinge of the control surface helps the pilot to move it. The more the pilot deflects the control surface, the greater the angle between the surface and the tab, and so more help is given when more is needed.

In all balanced controls, the designer must be careful to avoid fully balancing the surface, or the pilot will lose the " feel " of the control.

Trimming Devices.

The reader will remember that tailplane and elevator provide the means whereby, in steady flight, the pilot compensates for any residual moment that the forces of Lift, Drag, and Thrust may have about the Centre of Gravity. In other words, the tailplane and elevator are used to " trim " the aircraft for various conditions of steady flight. With a more complete knowledge of how the control surfaces work, this subject of trimming is worth a second thought.

One method, already mentioned, by which the load on the tailplane can be varied, is by altering the angle of the tailplane as a whole; but with an elevator capable of changing the effective camber of the

tail surfaces, there is usually no need to resort to this device. The only trouble now is that the pilot must apply continuous pressure to the control column to preserve the trim of the aircraft. Not only is this tiring on a long journey, but it makes the aircraft less easy to handle. If only there were some means of holding the elevator in the desired position, which would still leave the pilot full control!

This is exactly what the trim tab does. These tabs are small movable surfaces hinged to the trailing edges of the control surfaces and looking like balance tabs. For longitudinal trim, the tabs form part of the trailing edges of the elevators. If the aircraft is nose heavy, then the pilot reaches for the small lever or handle that is linked to

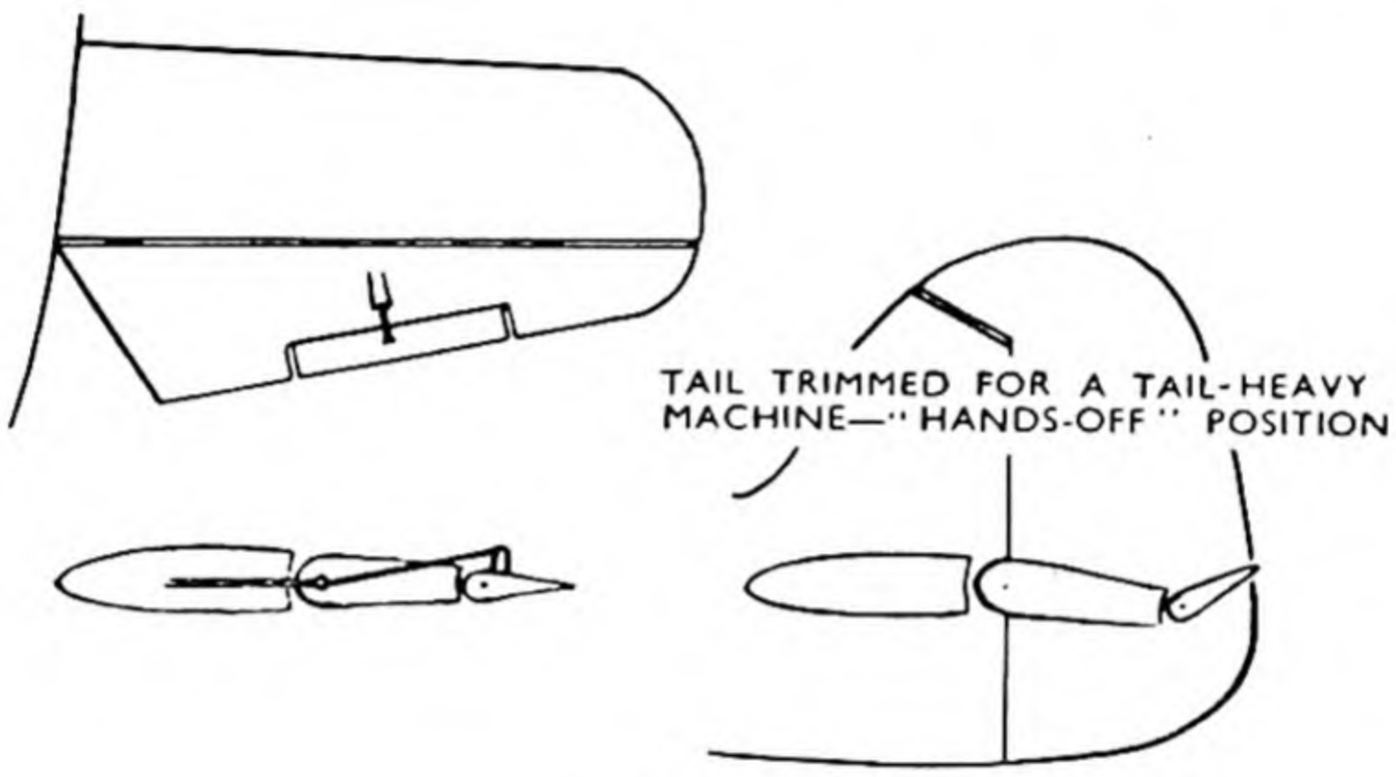


Fig. 61

this trim tab in the cockpit and gives a slight turn to set the tab at an angle to the elevator. The airflow past this tab will deflect the elevator the opposite way to the tab. As in this case the pilot wishes to hold the elevator up a little, he will turn the trim tab downwards. The equilibrium of the aircraft is thus restored and the aircraft is trimmed. The action of the trim tab is illustrated in fig. 61.

Trim tabs are often fitted to the rudder. They are useful for correcting any tendency of the aircraft to yaw, such as might be introduced by the failure of one of the engines of a multi-engined aircraft. Even a single-engined aircraft sometimes refuses to fly straight without slight pressure on the rudder bar on one side. The rudder trim tab relieves the pilot of the necessity for maintaining this pressure by holding the rudder to one side for him.

Such trim tabs are often *fixed*, as distinct from the *adjustable* type that have so far been considered. Fixed tabs are not hinged, but since they are made of fairly soft metal, they can be bent to one side by the rigger on the ground to correct for any bias that the aircraft may have when flying normally.

Fixed tabs, or, less often, adjustable tabs, are occasionally found on the ailerons on one side or the other. They can be used to correct for the tendency for one wing to fly low. If the pilot found it necessary to jettison the petrol from one of the large tanks on the starboard side of the aircraft, then he could hold the aircraft on an even keel by lowering the port aileron and raising the starboard aileron. Deflecting a trim tab downwards on the starboard side would do this for him.

To summarize, it may be stated that *trim tabs are used to produce equilibrium in any attitude during steady flight, in order that the desired attitude can be maintained without effort on the part of the pilot.*

A certain amount of confusion arises between trim tabs and balance tabs because they look the same. They may look the same but they do not work in the same way, neither do they perform the same functions. The angle that the trim tab makes with the control surface to which it is attached does not alter when the pilot deflects the control. It provides a bias to the control surface. The angle which the balance tab makes with the control surface is not controlled directly by the pilot, and increases as the control is deflected more and more.

It is quite possible, however, for one tab to be arranged to fulfil both functions, and in some aircraft these trim-cum-balance tabs are used. The pilot sets the trim, and thereafter the tab acts as a balance tab, but with a bias.

The trim tab exerts such a powerful leverage about the hinge of the control surface to which it is attached that considerable care should be exercised in its use. It should never be used alone in the place of the usual controls to manœuvre the aircraft. As an example, the use of the elevator control tab alone to pull the aircraft out of a steep dive might easily tear the elevator from its hinges.

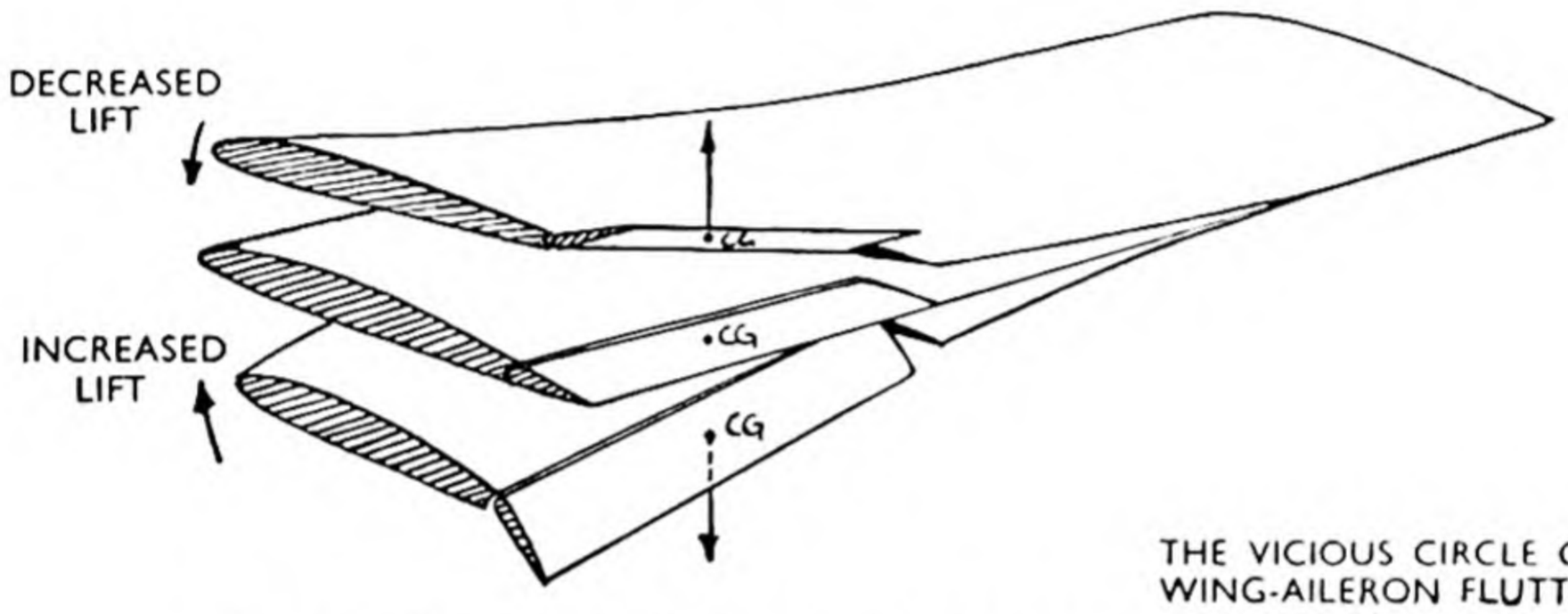
Mass Balance and Flutter.

In modern aircraft there is the chance of a phenomenon called "flutter" occurring at high speeds. This happens when two types of vibration become linked together in such a way that one feeds energy into the other, and the amplitude of each vibration increases to a point where structural failure may result.

For instance, if the aileron control wires are slack, vibration of the ailerons up and down is possible. The elasticity of the wing permits some oscillation of the wing-tips up and down: such flexibility is inseparable from the mechanical structure, and is like the flexibility of a long ladder. Neither vibration by itself is at all dangerous, but at high airspeeds it is possible that one will feed the other until either the control surface or the whole wing breaks off.

It is not difficult to understand how this vicious circle is built up. When, during the course of its oscillation, the wing reaches the limit of its downward movement, the inertia of the aileron causes it to carry on, and the loose aileron wires allow it to do so. The aileron, therefore, twists about its hinge. At the other extreme of the wing's movement, the aileron is flung upward. In this way the wing " shakes " the aileron. This feeding of energy from the wing vibration to aileron vibration may be called " *inertia coupling* ".

Now returning to that moment at which the aileron is flung downwards by the wing, it can be understood that the depressed aileron gives an increased lift to the wing, and this extra lift acts as an



THE VICIOUS CIRCLE OF WING-AILERON FLUTTER

Fig. 62.—How wing and aileron may help one another to vibrate

upward impulse, helping the vibration of the wing in exactly the same way as small correctly timed impulses will cause a child's swing to swing in wider and wider arcs. At the upper limit of wing movement the upturned aileron will give decrease in lift, acting as a downward impulse: this swing has two helpers instead of one. In this way the aileron vibration feeds energy to the wing vibration, and this may be called " *aerodynamic coupling* ".

The train of events may thus be set down:

Wing Vibration

Inertia Coupling ↘ ↖ Aerodynamic Coupling

Aileron Vibration

and is illustrated in fig. 62.

The circle must be broken at one of its links if flutter is to be prevented. One way is to attack the wing vibration link and stiffen the wing structure: increased weight sets a practical limit to this. Another way is to make the aileron vibration difficult by using a more

positive control than is provided by the wires, but even this may only result in the whole control mechanism being embroiled in the vibration and the control column shaken from the pilot's hand.

A third way is to break the chain at the link "inertia coupling" by the use of mass balance. An accurately calculated weight, usually of lead, is so fixed to the control surface in front of the hinge line that the centre of gravity of the complete unit lies along the hinge line instead of, as previously, at some point behind it. This provides a cure, for the aileron now no longer tends to turn when the wing "pulls up" at the end of its swing. Sometimes the mass is on the end of a short rod, but sometimes it is hidden inside that part of the

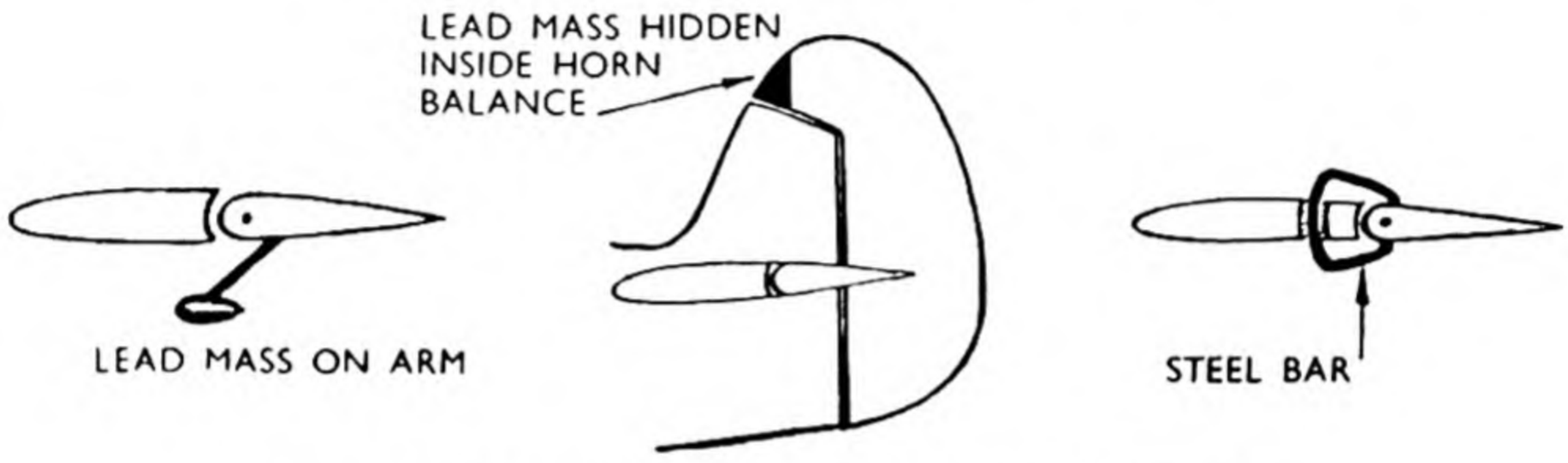


Fig. 63.—Three ways of mass-balancing control surfaces

surface that lies in front of the hinge for the purpose of providing aerodynamic balance (see fig. 63). Occasionally it is fastened to one of the rods linking the control surface to the control column, and thus lies inside the fuselage.

Wing-aileron flutter has been used as an example, but there are other places in the aircraft where flutter may occur. It is sometimes found necessary to attach mass balances to elevators, rudders, and even tabs.

Mass balance must not be confused with aerodynamic balance. The former deals with the prevention of flutter, whilst the latter is to make the control surface easier for the pilot to turn—two entirely different matters.

Flight at Slow Speeds.

It has already been noted that both stability and control are reduced at slow speeds because of the slower airflow, but there is more to it than just this.

At slow speeds, the wings of the aircraft are near stalling angle. Modern wing sections may not stall suddenly, and turbulence may occur over the trailing edge of the wing whilst it is smooth near the leading edge. The aircraft is not yet stalled, but the ailerons are in-

effective, and lateral control is lost. The pilot may move the stick through wide angles from side to side without its having any effect as far as banking the aircraft is concerned.

In the chapter on stability it was shown how lateral stability may easily be lost if a disturbance causes one wing to drop slightly when flying at slow speeds, and the aircraft may turn right over (p. 78). This was called autorotation. An attempt to use the ailerons when flying slowly may have exactly the same effect, for, with the wing near stalling angle, the effect of lowering one aileron may be completely to stall that wing. Autorotation will result and the aircraft will then go into a spin.

Spin.

It is comparatively easy by means of a model in front of a wind-tunnel to demonstrate autorotation, but difficult to show the subsequent spin, for the model aircraft is not free, as is the real aircraft, to drop through the air. With the real aircraft, the roll causes a yaw; the loss of lift causes pitching, and the aircraft descends with a corkscrew motion in which it turns about all three axes. During this motion the wings are stalled, and therefore the spin is not like a spiral dive, during which lateral control is retained. At one time spinning was thought to be a disastrous manœuvre, but, nowadays, in aircraft in which it is permitted, spinning is part of the pilot's training, and quite safe when carried out at the proper heights. Obviously one of the essentials of recovery from the spin is to decrease the angle of attack of the wings so that they are no longer meeting the air at an angle of attack greater than stalling angle: the other essential is to stop the rotation about the normal axis. So " stick right forward and full opposite rudder " is the rule for recovery from the spin.

QUESTIONS

1. Rewrite and complete the following table:

(*a*) Lateral control	about the ..... axis	in the ..... plane	by means of the .....
(*b*) Directional control	about the ..... axis	in the ..... plane	by means of the .....
(*c*) Longitudinal control	about the ..... axis	in the ..... plane	by means of the .....

2. What is meant by saying that a control surface is aerodynamically balanced? By diagrams or otherwise, describe three methods of aerodynamically balancing control surfaces.

3. (*a*) What is aileron drag, and what is its effect on the aircraft?

(*b*) Under what condition of flight is the effect of aileron drag most noticeable?

(*c*) Describe by diagrams or otherwise, and name two ways in which aileron yaw has been reduced.

4. Rewrite the following statements, correcting them if necessary:

(*a*) The lift force is always vertical.

(*b*) The axes of the aircraft are fixed relative to the ground.

(*c*) Lateral dihedral is the angle between the mainplane and the horizontal.

(*d*) An aircraft always stalls at the same true air speed in level flight, if the weight is unaltered and the flaps are untouched.

5. (*a*) Name two controls which shorten the landing run.

(*b*) Enumerate two advantages and two disadvantages of tricycle undercarriages.

(*c*) Name two aircraft with tricycle undercarriages.

6. (*a*) What is the purpose of mass balance?

(*b*) Describe two ways in which the mass balance is fitted to a control surface. Use diagrams.

7. In a two-engined aircraft the starboard engine fails. In order to maintain a straight course the pilot adjusts one of the trim tabs, and in order to maintain height he adjusts another.

(*a*) Which trim tab is used to keep a straight course, and which way is it moved?

(*b*) Which trim tab is used to maintain height, and which way is it moved?

(*c*) Draw a diagram of the control surface and tab in the second case, and explain how it works.

8. (*a*) What are ailerons and what is their function?

(*b*) Explain how an attempt to lift a dropped wing when flying very near to stalling speed may cause autorotation of the aircraft.

(*c*) What uncontrolled manœuvre will result from this autorotation?

9. (*a*) Rewrite and complete the following table:

	(1) Start bank to right.	(2) Pull nose up.
Control surface used:	.....	.....
What the pilot moves and which way:	.....	.....
Which way the control surfaces move:	.....	.....

(*b*) Why will the aircraft start to turn when the bank is applied?

10. (*a*) What is the purpose of aerodynamic balance?

(*b*) Draw diagrams to show three ways of aerodynamically balancing the rudder.

(*c*) What would be the effect of too much aerodynamic balance?

11. (*a*) For an aircraft in level flight, (1) a roll produces a yaw, (2) a yaw produces a roll. Explain why this is so.

(*b*) Use this explanation to explain the meaning of the term "spiral instability".

12. (*a*) If the starboard engine of a twin-engined aircraft fails, what movement of (1) the rudder bar and (2) the rudder will be necessary to make the aircraft fly a straight course?

(*b*) How might the pilot avoid having to keep pressure on the rudder bar under such circumstances?

13. (*a*) Describe the movements of the ailerons when the control column is moved to the left.

(*b*) Which way will the aircraft roll, and why?

(*c*) It may yaw momentarily in the opposite direction. Explain the cause of this.

14. An aircraft is flying level near its minimum speed.

(*a*) What do you know about the attitude of the wings?
(*b*) What effect will this condition of flight have on the lateral control, and why?
(*c*) Are the other controls affected? If so, why?
(*d*) In what two ways could the minimum speed of an aircraft in level flight be reduced?

15. The Tiger Moth is a biplane with *sweepback*, *forward stagger*, and *dihedral* on the lower wings. The rudder has *horn balance*, and the elevator has a *mass balance*. The ailerons are *differential*, and are on the lower wing only.

(*a*) Taking the underlined terms in order, say what the first three mean, and explain the reason for the last three.
(*b*) Why has the designer chosen to put the ailerons on the lower wings only?

16. (*a*) It is reported to the maintenance staff that an aircraft flies with the port wing low. There is a fixed trim tab on the starboard aileron. What will the rigger do to it to correct the flight of the aircraft?

(*b*) Explain how this will correct the fault.

CHAPTER VIII

Propellers

PARTS OF THE PROPELLER. VARIABLE-PITCH PROPELLERS. CONSTANT-SPEED PROPELLERS. SLIPSTREAM. PROPELLER TORQUE.

Parts of the Propeller.

The propeller or airscrew is a means by which the horse-power of the engine is turned to forward thrust. Each blade of the propeller is essentially a rotating wing, and the cross-section of a propeller is similar to the cross-section of the wing.

Some of the terms associated with the propeller are illustrated in fig. 64. The *root* of each propeller *blade* is fastened securely to the propeller *boss* at the centre. In all but the smallest aircraft this boss is covered by a light fairing, called the *spinner*, to reduce drag. The blade *tips* sweep out a circle the diameter of which is referred to as

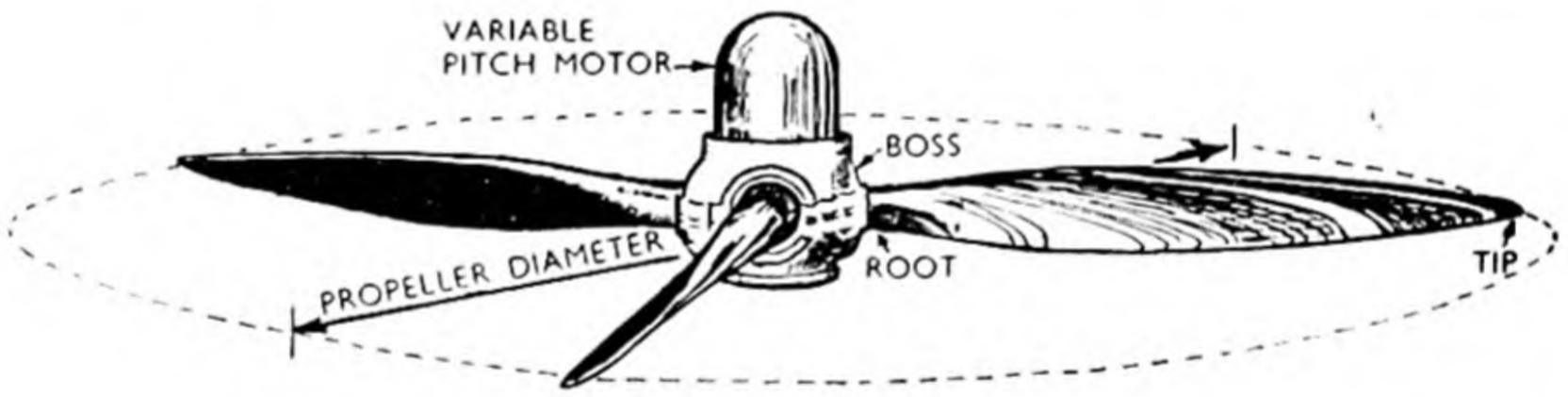


Fig. 64.—A three-bladed variable-pitch fully-feathering propeller

propeller diameter. If the propeller is in front of the engine, it is called a *tractor*; if behind, a *pusher*. If the direction of the rotation is such that, when viewed from the tail of the aircraft, the propeller goes from right to left over the top (anticlockwise), then it is a *left-hand* tractor or pusher; if the reverse, a *right-hand* tractor or pusher.

The actual velocity of any particular blade element (or cross-section) is a combination of the velocity given to it by its rotation about the propeller shaft, and its forward velocity at right angles to the plane of rotation due to the motion of the aircraft. The resultant of these two takes the blade element along a helical path, and, of course, the relative wind or airflow therefore meets the blade along the same path, in the reverse direction. If this helix, extended over the period of one revolution, is drawn on a cylinder made from a sheet of paper, and the paper afterwards unrolled, it can be seen that

the path of the blade element is laid out as a sloping straight line. This line is the hypotenuse of a right-angled triangle, of which the two short sides are the distance travelled forward by the aircraft during one revolution of the propeller, and the circumference of the circle swept out by the blade element in the same time. This is shown in fig. 65. It is usually easier to study the propeller movement " laid out " in this way.

The propeller blade is inclined to this helical path so as to present a positive angle of attack to the air, and in this way the air exerts a force on the blade (and the blade on the air), just as in the case of a wing in flight. This reaction may be split into two component forces

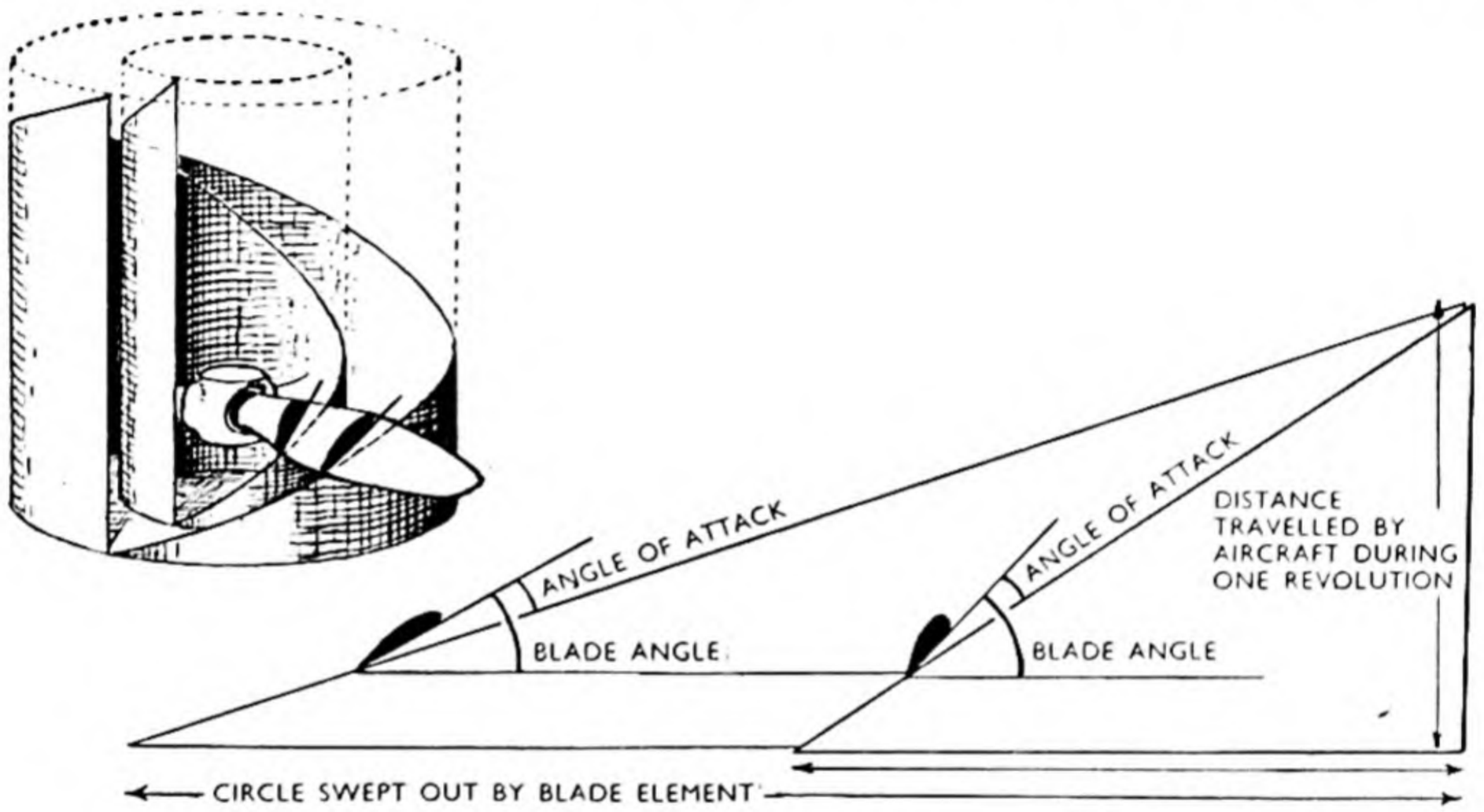


Fig. 65.—How propeller angle of attack varies with forward speed

at right angles to one another in the same way that the total reaction from a wing is split into lift and drag, only in this case the two chosen directions are parallel and perpendicular to the direction of motion of the aircraft and not to the airflow. The component in the plane of rotation of the propeller, when all the elements are added together, is the twisting force or drag that opposes the engine torque, and when the propeller is rotating at constant speed these two opposing twists are equal, and balance one another to produce steady motion. The forward-acting component, when the whole blade is considered, gives the forward thrust that balances the aircraft drag in steady flight. Ideally, each blade element lies at an angle of attack to the helical airflow that gives the greatest ratio of forward thrust to drag for economical flying.

Each part of the propeller travels forward the same distance during each revolution, but the circumference of the circle that each

point along the blade sweeps out when the aircraft is not moving depends on its distance from the centre of the boss. Therefore, as a reference to fig. 65 shows, the nearer the blade element is to the boss, the steeper the helical path it follows. If each part of the propeller is to attack the air to the best advantage, the angle made by the propeller and its plane of rotation must increase as it approaches the centre. This angle is usually measured between the flat underside of the blade (which acts as the chord for the propeller) and the plane of rotation, and it is called the *blade angle*. It is the variation of the blade angle throughout its length that gives the propeller its twisted appearance.

Variable-pitch Propellers.

The steepness of the path followed by any part of the propeller must vary with the forward speed of the aircraft. It follows that the angle of attack of each blade element must change with every change in forward speed. Fig. 66 illustrates this point, and shows how the angle of attack at small forward speed will be large (with no forward

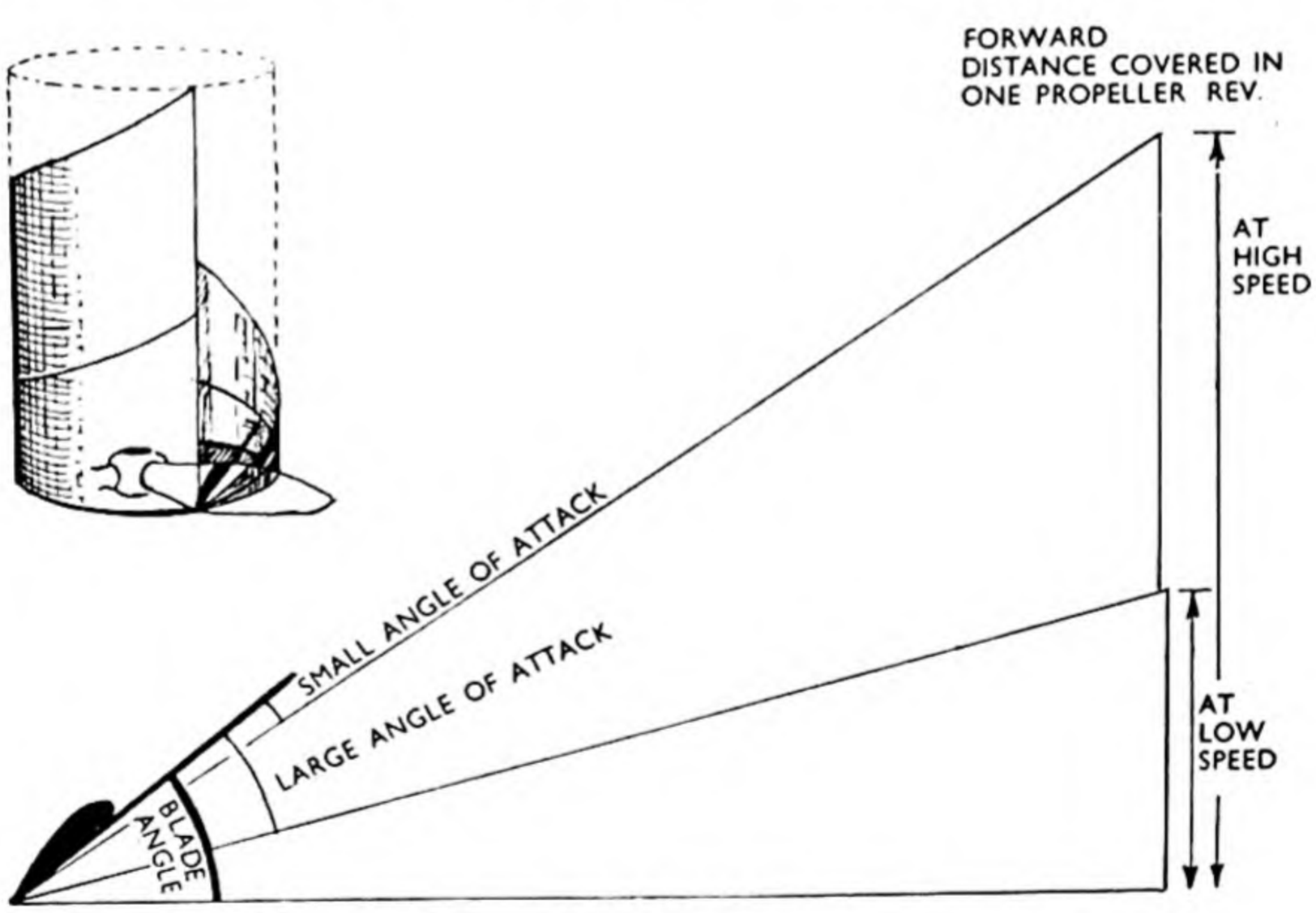


Fig. 66.—How propeller angle of attack varies with forward speed

speed it will equal the blade angle), whilst as the forward speed grows the angle of attack diminishes until a speed is reached where the angle is zero. Somewhere near this point the blades will be giving no forward thrust whatever. In a dive, the forward speed may rise to a value so great that the blades lie at a negative angle of attack to the airflow large enough for the propeller to give a backward-acting force

instead of a forward one. When this happens the air will turn the propeller, and the engine will " race " at high speed. The propeller is " windmilling ", and acting as a brake.

If the forward speed of the aircraft were always the same, it would be a simple matter to design an ideal propeller for which, at every point along its length, the angle of attack would be such as to give the greatest thrust for the least drag. But since the angle of attack depends on the forward speed, it is impossible with propellers of fixed pitch to maintain equal efficiency at all speeds, and so propellers are now commonly used in which the blades may be twisted about the propeller boss to give the best angle of attack over a wide range of speeds.

Sometimes the pilot may select either *fine pitch* or *coarse pitch*. Fine pitch, with the blades more nearly parallel to their plane of rotation, is used at slow speeds, i.e. for take-off and steep climb. It is also used as a precautionary measure in landing, so that the pilot may climb away again easily if need be. In coarse pitch the blades make a larger angle with the plane of rotation, and this is used in normal flight, in order that a large enough angle of attack may be maintained for efficient operation.

Variable-pitch propellers are most useful for high-speed aircraft, for at high speeds a large blade angle is necessary. With fixed-pitch propellers this would mean that at the beginning of the take-off, when blade angle and angle of attack are the same, the blades would be stalled: drag would be high, and thrust low.

Constant-speed Propellers.

Constant-speed propellers attempt to do more than use the propeller to the best advantage: they also try to get the best out of the engine. They fulfil the latter task better than the former. The pitch of the blades is controlled by a centrifugal governor which operates through an electric motor or uses the hydraulic power of high-pressure oil to change the angle of the propeller blades automatically. The object of this automatic adjustment is to maintain a constant rate of revolution of the propeller, and hence of the engine to which it is geared. The engine is therefore always working at the speed at which it is most efficient during normal cruising flight. The engine speed may be selected by the pilot, and for extra power a higher engine speed is used. The choice is in the hands of the pilot, but, once selected, the engine speed is maintained automatically by the governor and its associated mechanism.

In order to understand how the engine revolutions and the propeller's angle of attack vary together, consider the case of an aircraft about to take-off. The propeller blades will be in fine pitch, and so the load imposed on the engine will be no more than will limit the engine revolutions to the proper take-off value. As the aircraft gathers forward speed the pitch of the blades will increase, the angle of attack keeping at such a value as to give a constant load on the engine, and maintain constant engine revolutions. In this way the propeller is doing its best, and the engine is doing its best, and as a team they are working together to give the greatest forward thrust at the particular throttle setting. This is admittedly a simplified version of what happens, but correct in principle. The constant-speed device is very like the gearbox of a car, except that it is continuously variable and automatic.

Fully feathering propellers embody an additional refinement. If an engine is not working during flight the propeller will nevertheless rotate, forced round by the airflow. It will not, of course, be giving any forward thrust; on the contrary, whilst it is " windmilling " in this way, it will add to the aircraft drag.

By turning the propeller blades " edge on " to the direction of flight it is possible to avoid this windmilling of a damaged engine. This is called feathering the blades, and provision for feathering is provided in many variable-pitch systems. The advantages of feathering the propeller of a damaged engine are: firstly, further damage to the engine is avoided and vibration eliminated, and secondly, drag on the side where the damaged engine lies is decreased.

Slipstream.

Just as the wing throws the air downwards in order to produce its upward lift, so the propeller throws the air backwards to obtain its forward thrust. This backward stream of air is called the slipstream. If it were visible, it would look like a tube of approximately the same diameter as the propeller in which the air is twisting backwards along a helical path like a corkscrew, as in fig. 67. The slipstream may be of some use in providing airflow over the rear control surfaces at very low speeds. There is, however, one thing about it which makes it a nuisance. Owing to its helical path, it strikes the fin and rudder from one side, and gives the aircraft a tendency to yaw and swing. In the air this tendency may only be slight, and is sometimes overcome by setting the fin at a slight angle to the longitudinal axis of the aircraft. The off-set fin and rudder is one way of

overcoming the effect of slipstream; another is by the use of the rudder trim tab. The effect of slipstream is very pronounced with a powerful single-engined aircraft during take-off, and it is sometimes necessary for the pilot to apply full rudder in order to counteract the tendency to swing.

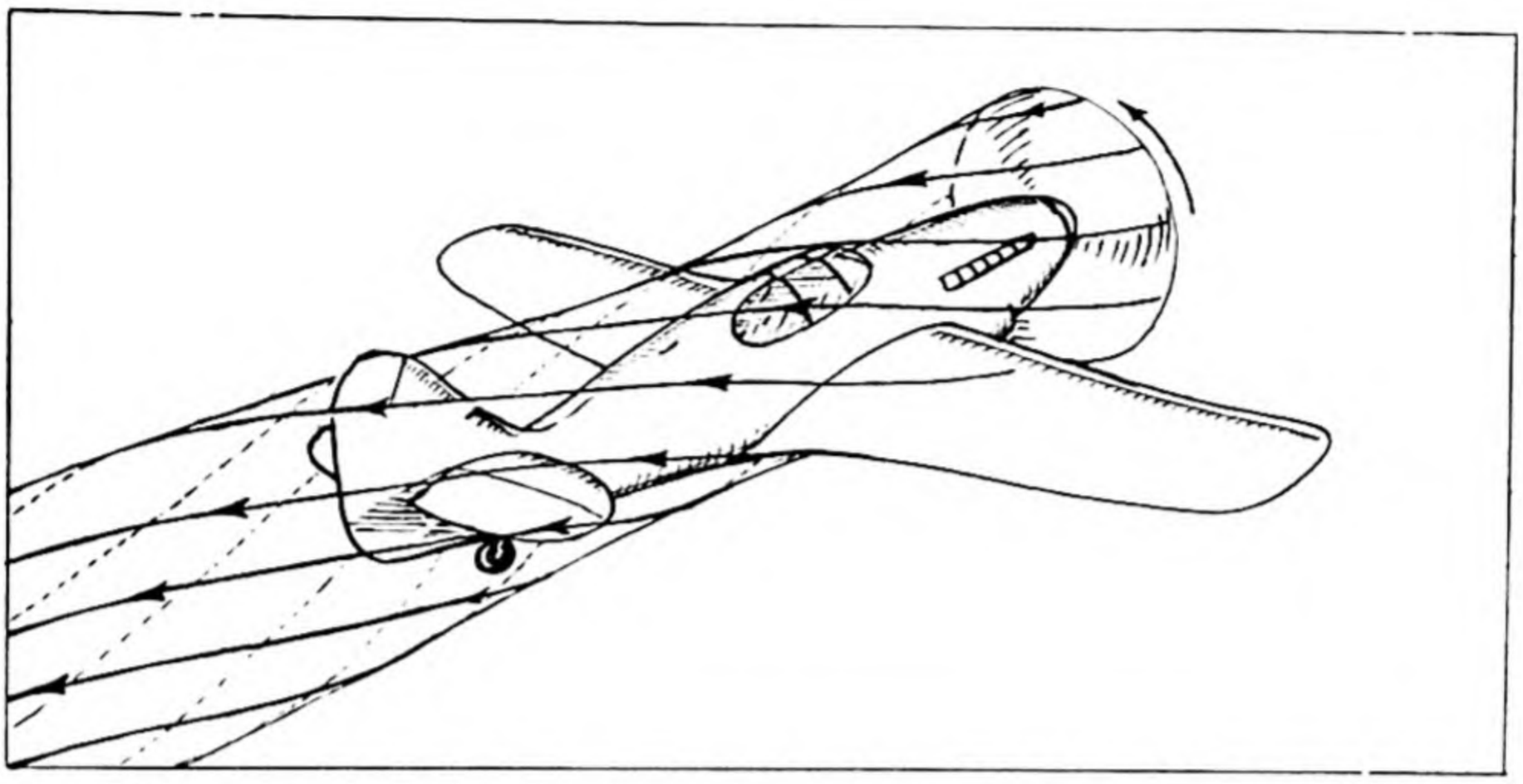


Fig. 67.—How the spiral slipstream strikes the fin and rudder on one side

Propeller Torque.

To every action there is an equal and opposite reaction, so that when the engine turns the propeller around, the propeller tries to turn the engine and the aircraft around the opposite way. Hence there is a tendency for the aircraft to roll or fly one wing low. It is noticeable in small aircraft with very powerful engines. Several ways of overcoming it are in use. Sometimes more weight is put on one side than the other; sometimes the angle at which the wing is fitted to the aircraft or the area of the wing is less on one side than the other. With biplanes, it was possible to adjust the bracing wires to give " wash-out " on one wing. This meant that the angle of attack of the wing was decreased towards the wing-tips by a slight twist of the wing.

QUESTIONS

1. (*a*) Why is it necessary for the pilot of a powerful single-engined aircraft to apply rudder when taking off?

(*b*) Why were some biplanes rigged with wash-out on one wing?

(*c*) With a two-pitch propeller, does the pilot use coarse pitch:

1. For take-off?
2. For cruising?
3. For steep climb?

2. (*a*) On a certain aircraft the rudder points along the longitudinal axis but has a cambered section similar to that of a wing. Why is this so?

(*b*) Give two advantages to be gained from fully feathering the propeller of a damaged engine.

3. Explain why an aircraft with a powerful engine may tend to yaw during take-off.

Part II—ENGINES

CHAPTER IX

The Aircraft Engine: How It Works

DEFINITION OF AN ENGINE. SPECIAL REQUIREMENTS OF AN AIRCRAFT ENGINE. THE INTERNAL-COMBUSTION ENGINE. COMBUSTION. FUEL. HEAT ENERGY. ELEMENTS OF THE ENGINE. THE FOUR-STROKE CYCLE. TIMING. VALVE MECHANISM. THE COMPLETE ENGINE. MULTI-CYLINDER ENGINES.

Definition of an Engine. Special Requirements of an Aircraft Engine.

An engine is a machine for converting the heat energy derived from the burning of fuel into useful mechanical work. A large proportion of the heat produced by man for his own convenience is used in this way. The work done may be used to lift bodies too heavy for man's unaided strength, for cutting, shaping, and hammering the materials he uses for making things, or for transporting these and himself from place to place.

The aircraft engine, the railway engine, and the motor-car engine are used in this last way, but whereas, with the railway and automobile engines, the power unit is concerned only with propulsion, the case of the aircraft engine is somewhat different. With heavier-than-air machines the power unit is necessary in order that they may be capable of sustained flight, and without it the aircraft must descend to the ground. For this reason engines that are to be used for aircraft must, above all, be reliable; that is to say, they must be capable of running for long periods of time without failure.

Amongst other requirements that the aircraft imposes upon its engine, extremely light weight in proportion to the power developed is of prime importance. The engine in the original Wright Brothers' aircraft, the first successful flying-machine, weighed 16 lb. for each one of its 15 horse-power. Continued research and experiment have resulted in modern aircraft engines that weigh far less than this in proportion to the power they develop. In recent years the aero-engine designer has sought to produce engines that would weigh only 1 lb. per horse-power, and now this goal has been achieved and passed.

The engine that provides the power of 2220 horses for the Typhoon fighter weighs only about 1 lb. per horse-power, and some of the larger air-cooled radial engines have already improved on this figure.

Perhaps the third most important requirement of an aircraft engine is economy in fuel consumption. This is chiefly necessary from the point of view of reducing the weight of fuel to be carried, for the more fuel, the less the passengers, freight, or bombs that can be carried, but it is also important in commercial flying so that the cost of operation may be kept as low as possible.

Other requirements of the aircraft engine are compactness, low cost and, in war-time, the fewest man-hours for its construction. The minimum time necessary for maintenance and repair, freedom from vibration, the ability to vary its power output over a wide range of values are important factors, and last, but not least, the engine must be able to deliver adequate power when working in the thin air met with at high altitudes.

All this impresses upon us the fact that the aircraft engine calls for an ingenuity in design, an excellence of materials, and a skill in manufacture beyond anything required in any other type of prime mover. The aircraft engine is, in fact, the aristocrat of heat engines.

The Internal-combustion Engine.

The first engines made use of coal or wood to turn water into steam, and this steam was made to do work by forcing a piston along the cylinder into which the steam was led.

The aircraft engine now in almost universal use uses petrol, or, sometimes, heavy oil.

The most important difference between these two types of engines, however, lies in the fact that in the case of the aero-engine the combustion takes place, and the heat is generated, inside the engine itself. Such an engine is called an *internal-combustion engine*.

Suppose an ordinary air-pump, such as is used for pumping up the tyres of bicycles, is immersed in hot water, with the pump partly full of air, as in fig. 1(*a*), and the air outlet plugged. Suppose, too, that someone is holding the handle of the pump, and keeping the plunger in its place half-way down the cylinder or barrel. As the air becomes hot it may be felt trying to push the plunger along the cylinder. This is because the pressure of the air inside has risen and is exerting considerable force on the piston or plunger. If the handle is released, the piston will be pushed along the barrel by this force. The hot air will expand as this happens and its pressure will fall to a normal value.

The piston of an internal-combustion engine is moved in a similar way, except that in this case the air is heated from inside the cylinder by the combustion inside it of a suitable fuel (fig. 1(*b*)).

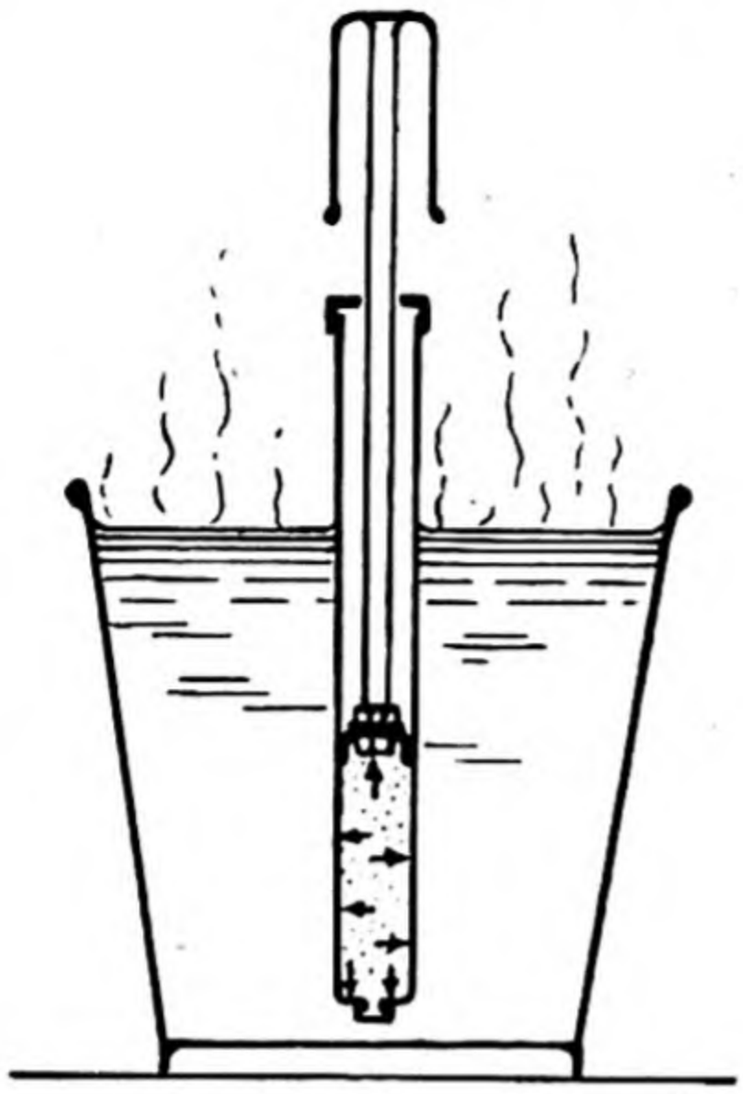


Fig. 1*a*

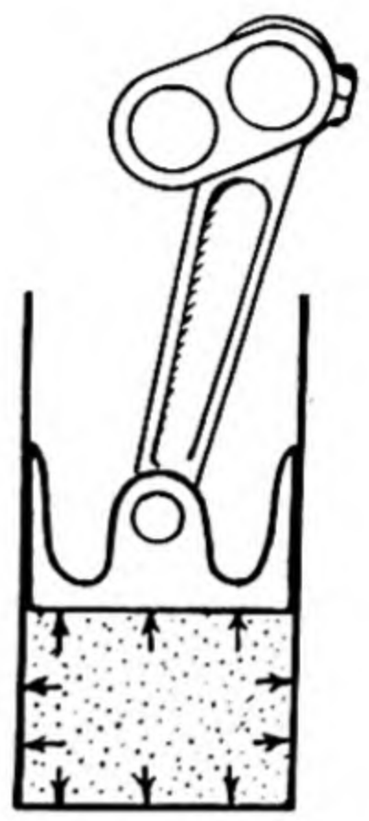


Fig. 1*b*

Combustion.

Combustion is the name given to the chemical combination of certain elements—usually carbon and hydrogen or compounds of these two—with oxygen. Ordinary air is a mixture mainly consisting of the gases oxygen and nitrogen, in a proportion of 1 part of oxygen to 4 parts of nitrogen by volume. Air provides a ready source of one of the essential elements in the process of combustion, and in nearly all cases of burning that are commonly met with; this is where the oxygen comes from.

It must be remembered, however, that experiments have been carried out with chemical compounds containing oxygen, and even pure oxygen compressed into a liquid has been used to provide a combustible mixture for engines.

The carbon and hydrogen may be found in many forms. Paper is a hydrocarbon and burns readily in air. So do wood, coal, and many fats and oils. Sometimes the hydrocarbon is in the form of a gas, and coal-gas is a well-known example.

In all cases the chemical combination that is called combustion is accompanied by the release of a considerable amount of heat. This is the essential characteristic of the process, and therein lies its importance. This heat is energy, and the importance of combustible materials, wood, coal, oils, lies in the fact that they constitute nature's great

storehouse of energy. But it is important to remember that without the oxygen in the air this energy could never be released.

The hot products of combustion of hydrocarbons are the same in all cases. The carbon forms gaseous carbon dioxide, and, occasionally, if the supply of air is insufficient, the poisonous carbon monoxide or even solid carbon is formed. The hydrogen combines with the oxygen to give water, which, because of the high temperature associated with the process, is in the form of steam. Proper steam, as distinct from the white cloud of water droplets that most people call steam when they see it at the kettle's spout, is an invisible gas, but there is no doubt about its formation in the process of combustion. If a bar of iron is thrust into a flame from a gas burner, but withdrawn before it has had time to become warm, the condensed water droplets are clearly visible on its surface.

In addition to the products of combustion mentioned, the nitrogen of the air will be left unchanged chemically, but heated by the combustion that has taken place.

Fuel.

The type of fuel that is burnt inside the cylinder must play an important part in the character and performance of the engine. The fuel most commonly used in aero-engines is petrol, which is a mixture of a number of hydrocarbons, forming a very volatile liquid. It is obtained from the crude oil found in abundance at various depths below the earth's surface in many different parts of the world. As it gushes from the well this crude oil is a dark-brown fluid. In the process of refining, it is distilled at atmospheric pressure. Petrol is the most volatile of the crude oil's various constituents; that is to say, the hydrocarbons in petrol boil at lower temperatures than the other constituents, and therefore evaporate first.

Nowadays, the refining of aviation petrol is a complex process involving not only distillation, but also chemical treatment at high temperature and pressure. During this process some of the less volatile fuel molecules are broken down or "cracked", and the result is a partly synthetic, or artificial, fuel which is better than that obtained by simple distillation alone. Various members of the alcohol group are also used. An alcohol molecule contains oxygen in addition to carbon and hydrogen. Certain aviation fuels contain, in addition to alcohol, small quantities of special chemicals, of which tetra-ethyl-lead is an example, known as *fuel dopes*. These are the special anti-knock or high-octane fuels (pp. 124 and 125).

Heat Energy.

The purpose of the fuel is to produce heat. Heat is one form of energy, and it is energy that is required to turn the propeller against the drag forces trying to stop its rotation. Amongst easily obtainable fuels, petrol gives more heat, weight for weight, when burnt than any other common substance, and the heat content of the other products of crude oil distillation is about the same.

Elements of the Engine.

The cylinder of the internal-combustion engine is filled with a mixture of petrol vapour and air in a definite proportion, and at the right moment the mixture is ignited, and burns very rapidly, when the piston is near the closed end of the cylinder, and the volume in

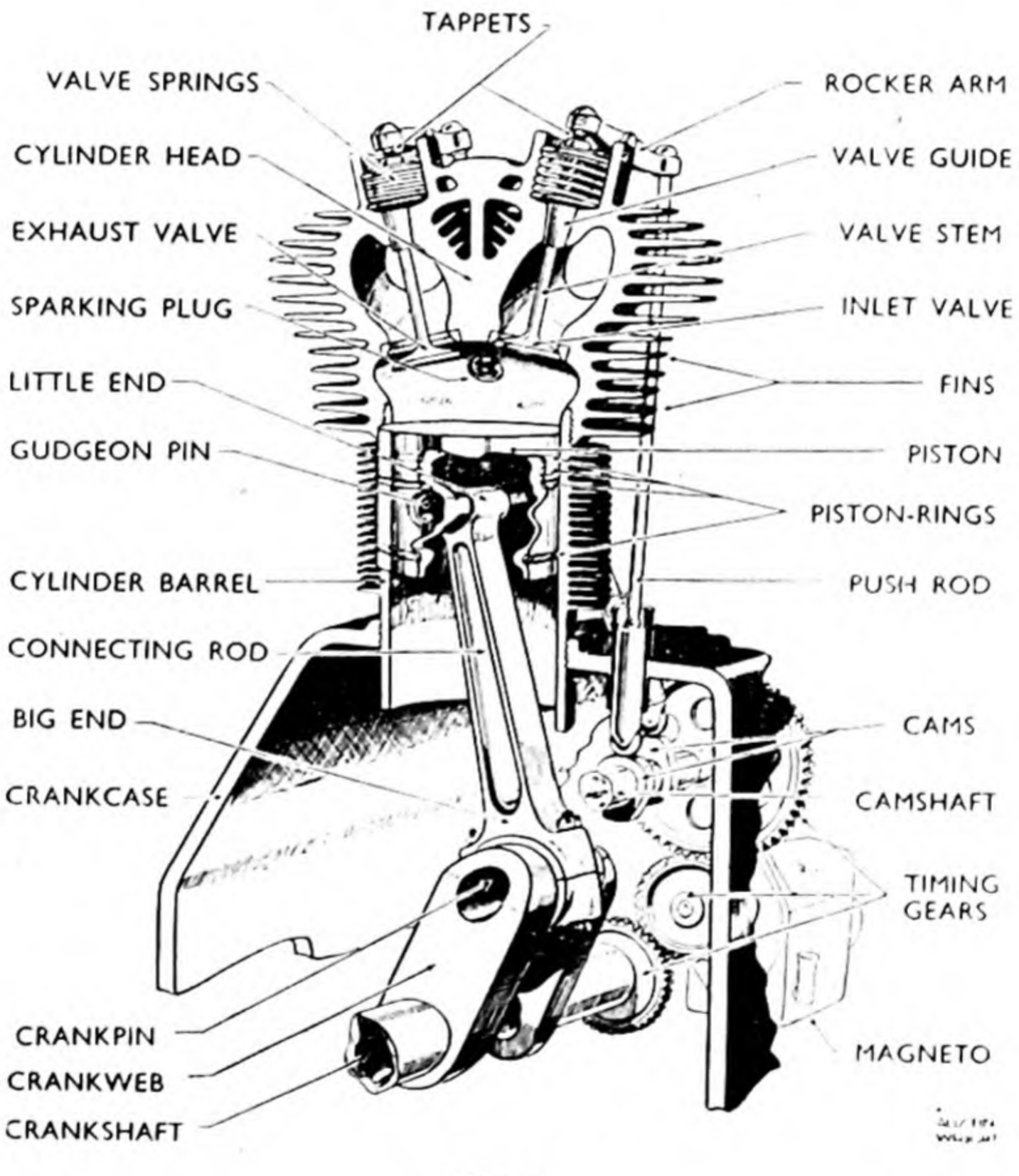


Fig. 2

which the combustion is taking place is small. As a result of the heat released by the burning, the carbon dioxide, water vapour, and the unchanged nitrogen are at a very high temperature, between 1500° C. and 2000° C. Since this rise of temperature takes place in a con-

fined space, the pressure that these gases exert on the cylinder walls and piston is also high, and may reach 700 lb. per square inch in modern engines. This pressure forces the piston along the cylinder, and so mechanical work is done.

The cylinder of an aero-engine (fig. 2) is made in two parts. One may imagine the *cylinder barrel* as a wide steel tube between 4 in. and 6 in. in internal diameter or " bore ", and about 11 in. long. It is

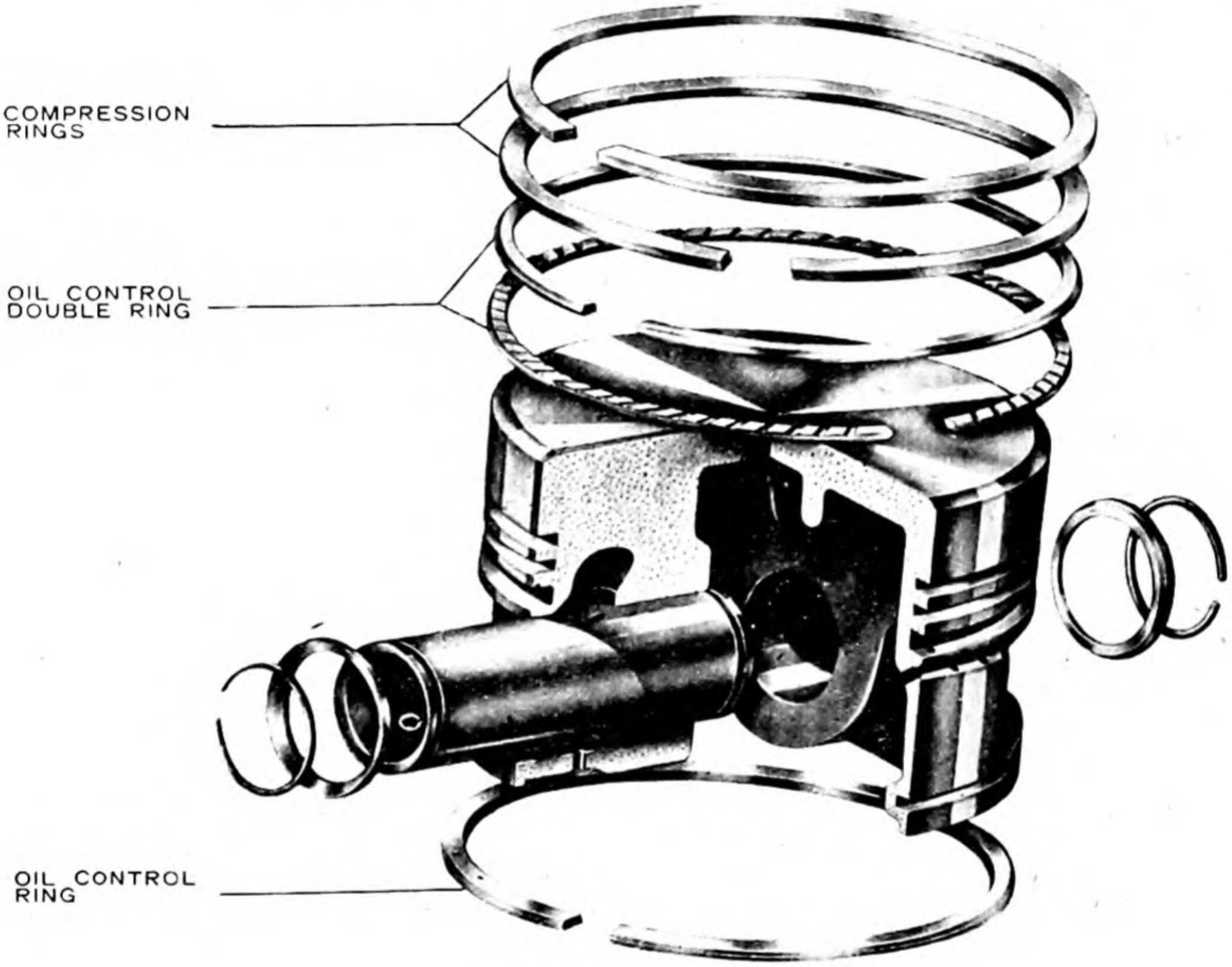


Fig. 3.—Piston assembly

(*By courtesy of the Bristol Aeroplane Co.*)

closed at one end by the *cylinder head*, a casting of light alloy and good heat-conducting properties. Inside this cylinder slides the light aluminium alloy piston upon the *crown* of which the gases exert their force after being heated. The space thus enclosed is called the *combustion chamber*.

In figs. 2 and 3 several grooves will be noticed round the side of each piston, in each of which are fitted *piston rings*. These are made of cast iron, which remains springy even at the high temperatures at which the engine operates. The rings are not complete but " split " at one point, so that they may spring outwards and fit snugly against

the cylinder wall. Those nearest the combustion chamber, usually three in number, are referred to as *compression rings* and prevent leakage of the high-pressure gases (or " blow-by ") past the piston. They, therefore, *seal* the combustion chamber. The others, one or two in number, are specially shaped in cross-section, and often have holes in them leading to holes behind in the piston. These are called *oil-control* or *scraper rings*, and as their name implies they control the oil, by spreading it evenly on the cylinder walls, and removing excess through the holes. This excess then drains away.

In the cylinder head there are openings for the fresh mixture to enter and for the spent gases to leave. The former, the *inlet port*, is

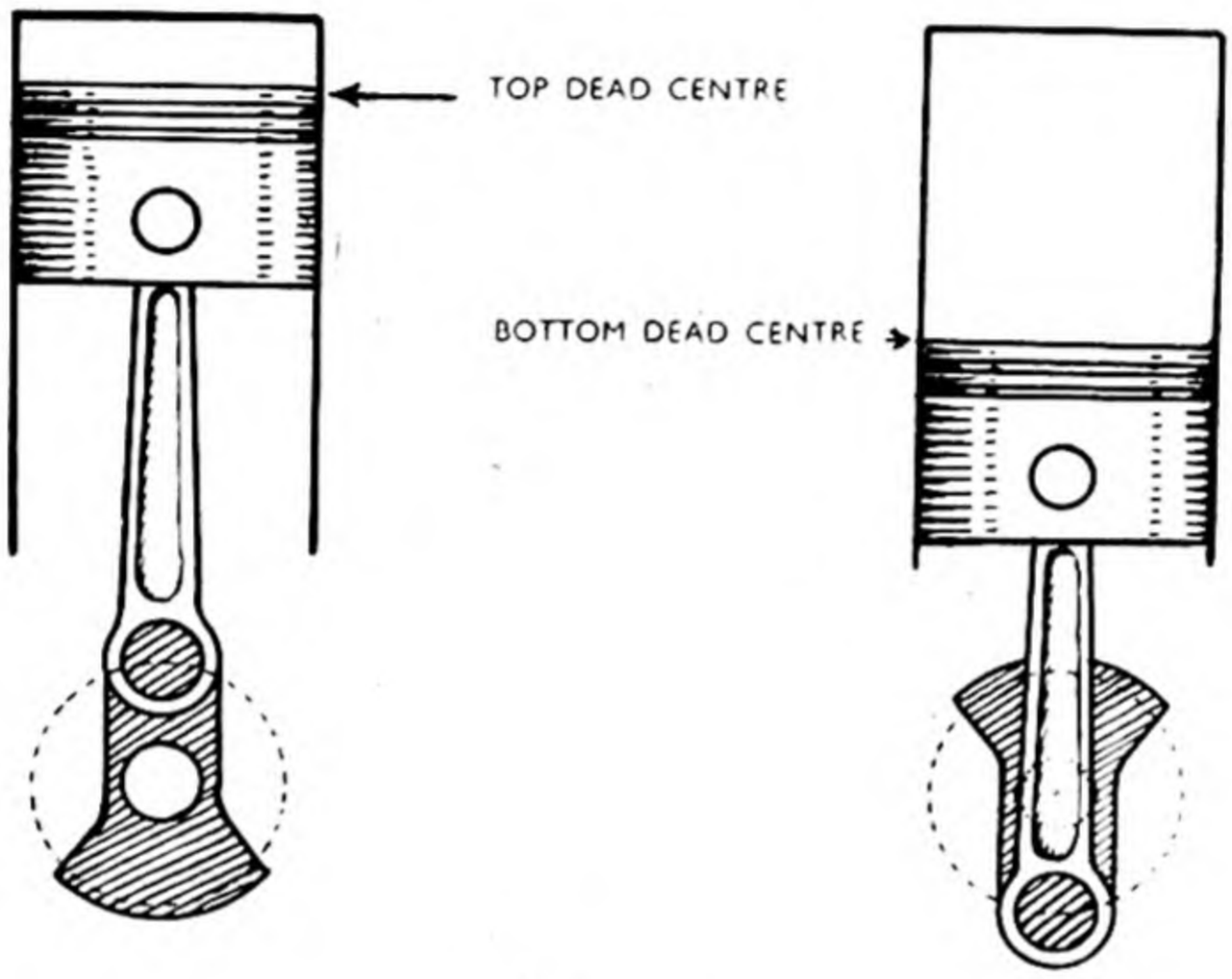


Fig. 4

closed by the *inlet valve*, and the latter, the *exhaust port*, is closed by the *exhaust valve*. A *sparking plug* is inserted through the cylinder head, and this ignites the petrol-air mixture at the right time.

The piston moves up and down the cylinder with a *reciprocating motion*, but a *rotary motion* is required to turn the propeller. The *connecting rod* serves to turn the reciprocating motion of the piston to a rotary motion of the crankshaft. The way this is done is shown in fig. 2.

When the piston is at the full extent of its travel, and nearest the cylinder head (fig. 4), its position is referred to as Top Dead Centre (T.D.C.); at the extreme position farthest from the cylinder head the piston is said to be at Bottom Dead Centre (B.D.C.). The *gudgeon pin* or *wrist pin* links the piston and the connecting rod. At the *big end* of the connecting rod is the *crank pin*. Together with the *crank web* and the main bearing, these make up the *crankshaft* (fig. 2).

The radius of the circle swept out by the centre of the crank pin, i.e. half the extent of the piston movement, is called *throw*.

All these new names may seem unnecessarily troublesome, but if pictures of engines are examined, and, if possible, an engine itself, the reader to whom engine parts are unfamiliar will soon be able to visualize them when they are mentioned. Until he can do so, he cannot learn much of the manner in which the engine works.

THE FOUR-STROKE CYCLE

Obviously, it is not sufficient for the cylinder to be filled with mixture, the mixture burnt, and the piston forced down the cylinder once only. The process must continue to repeat itself in cycles. A cycle of operations starts from any position of the piston, and finishes when the piston next reaches the same stage in the sequence of operations.

The aero-engine operates on the four-stroke cycle (fig. 5). The term *stroke* covers the movement of the piston from T.D.C. to B.D.C. or B.D.C. to T.D.C. During one stroke the crankshaft turns through 180°. During one cycle of the engine the crankshaft turns through two complete revolutions, i.e. 360°, and the piston makes four strokes.

(*a*) *INDUCTION STROKE.* During this stroke the inlet valve is open and the exhaust valve, except just at the beginning, is closed. The fresh mixture of air and petrol is entering through the open inlet port, and the piston is moving down the cylinder. The inlet valve is closed at the end of the stroke.

(*b*) *COMPRESSION STROKE.* Both valves are closed. The piston is moving towards T.D.C. and the gaseous mixture is being compressed. The compression of the gases causes some increase in temperature.

(*c*) *POWER STROKE.* Both valves are still closed. Just before T.D.C. a spark passes across the points of the sparking plug and ignites the gases. They burn rapidly and the gaseous products of combustion, together with the nitrogen, all at high temperature and pressure, exert a considerable force on the piston, forcing it down the cylinder. If any stroke is more important than the others, it is this, for it is the only *working stroke* of the cycle.

(*d*) *EXHAUST STROKE.* When the gases have given up nearly all the available energy, the exhaust valve opens and the rising piston forces them through the exhaust port. As the piston approaches

T.D.C. near the end of this stroke, the inlet valve opens and the cycle starts again. Fig. 5 shows the four strokes.

It is to be noted that only one stroke out of four is a working stroke. It may be difficult to realize at first why the engine continues to turn during the other three strokes, but this is no more remarkable

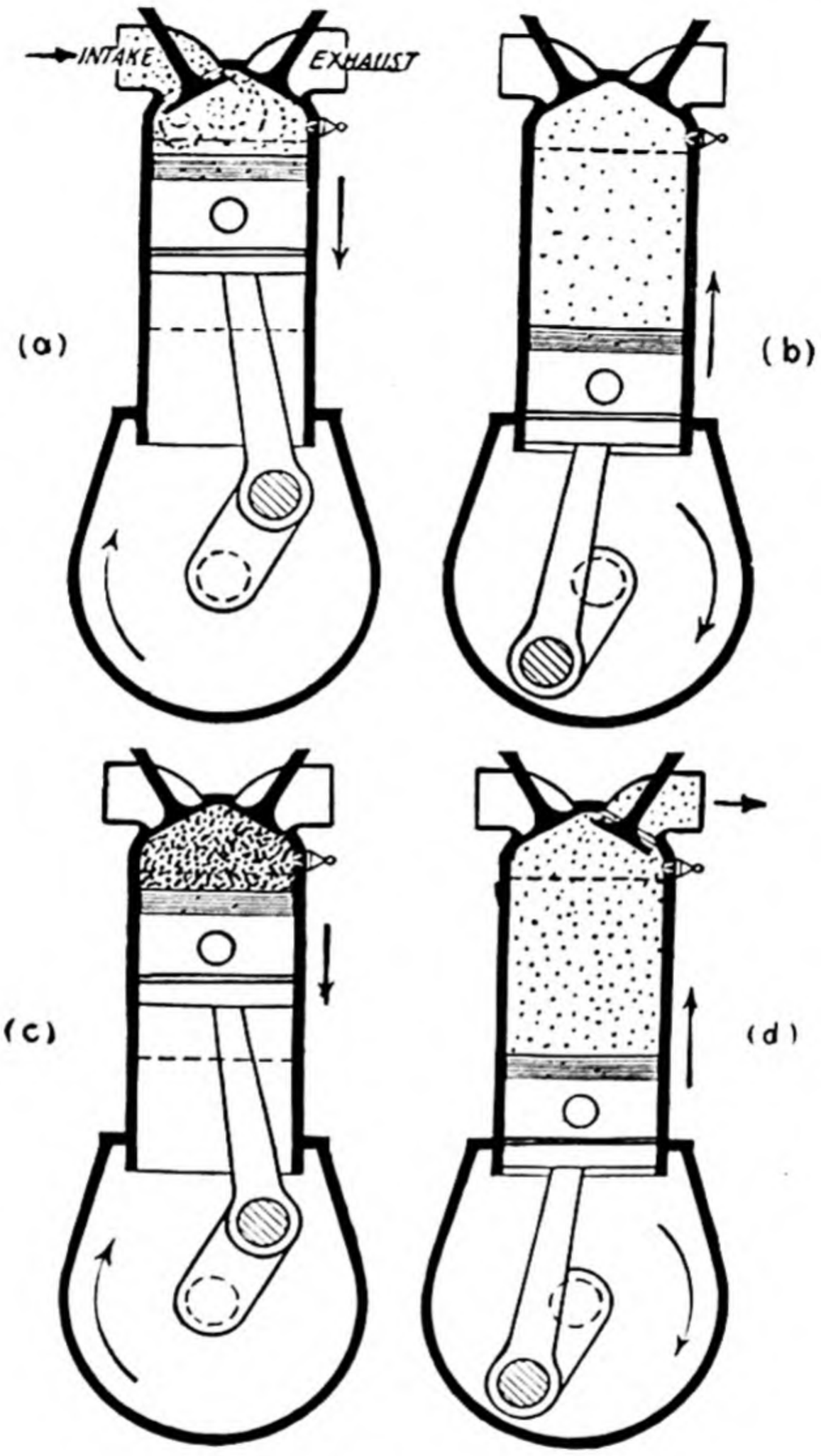


Fig. 5

than the fact that a bicycle should travel along smoothly when the cyclist is pedalling. The piston gets its momentum from the heavy crankshaft and the propeller fastened to it, in the same way as the bicycle uses the stored energy in its rotating wheels and the energy of its forward motion to carry it along smoothly between the pedal strokes, and even for some time after pedalling has ceased.

It must also be remembered that whilst only a single cylinder has

been illustrated so far, the modern aero-engine has many cylinders, and that, in such a multi-cylinder engine, some cylinder is always working on the power stroke, pushing the piston down and driving the crankshaft round.

Timing.

The valves must open and close, and the spark occur, at just the right time in each cycle. This is achieved by *timing gear* driven from the crankshaft, operating the valve mechanism and the means of spark production.

It would seem at first sight that the valves should open or close, and the spark occur, at B.D.C. or T.D.C. exactly, but in practice

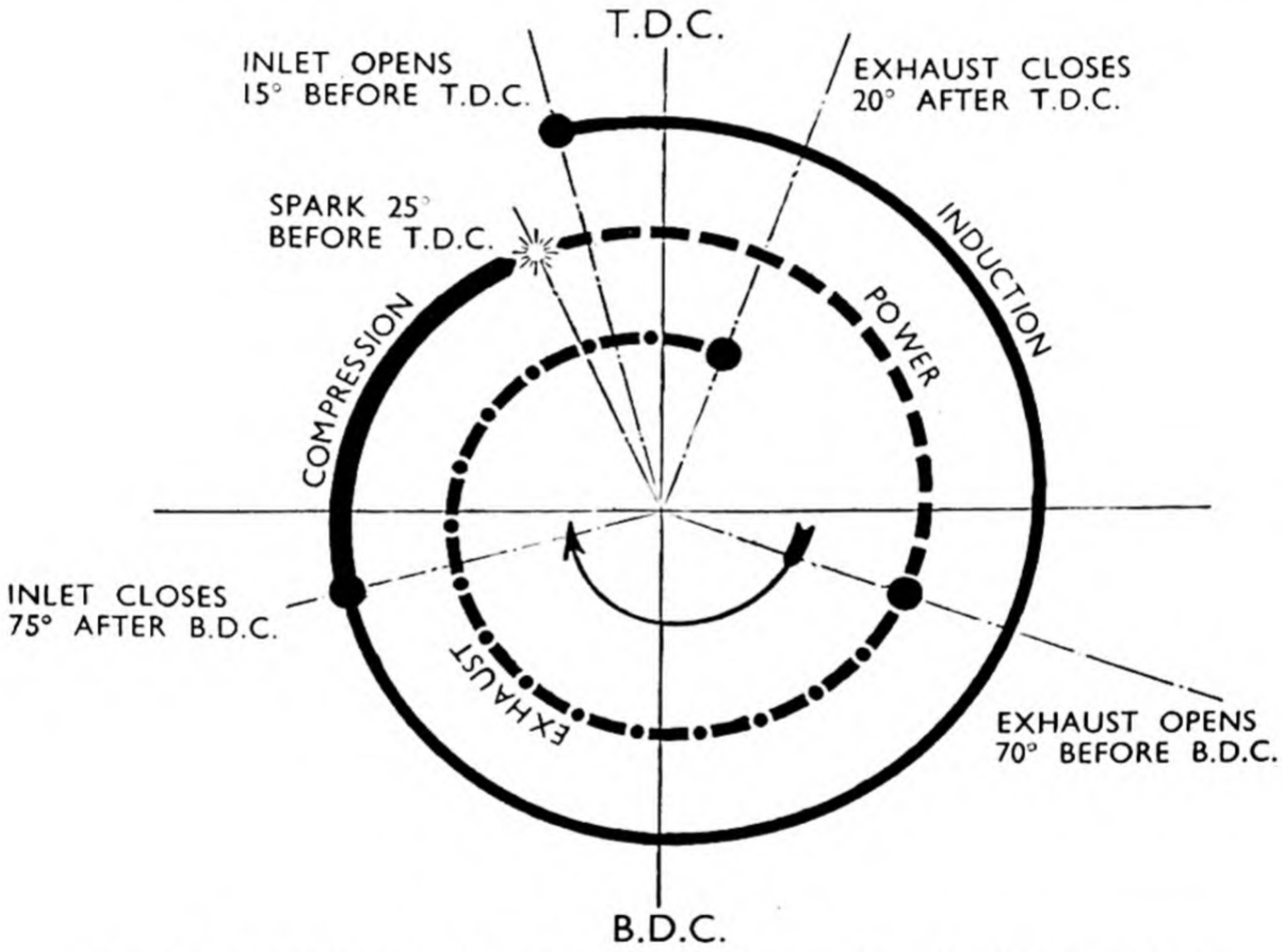


Fig. 6.—Typical four-stroke timing diagram. Arrow shows direction of rotation

better results are obtained by opening the valves early (*valve lead*) and closing them late (*valve lag*) and by having the spark occur before T.D.C. (*spark advance or ignition advance*).

It is usual to refer to these in terms of angular movement of the crankshaft, and the typical timing diagram (fig. 6) shows how this can be represented.

The reasons for modified timing are as follows:

1. The inlet valve begins to open before T.D.C., because it is essential that the valve be fully open when the piston starts

to move down the cylinder, so that as much mixture be drawn in as possible.

The momentum of the gases causes them to continue to pour in after the piston has passed B.D.C., and the inlet valve closes when the piston would start to push them out again if the valve were left open longer. The inlet valve, therefore, opens before T.D.C. and closes considerably after B.D.C.

2. The spark occurs early, because the charge should be burnt and the temperature and pressure of the gases be at their highest at, or very soon after, the piston passes T.D.C. In this way, full use is made of the force exerted by the gases in the working stroke.
3. By the time the piston is nearing B.D.C. the pressure of the gases has fallen, owing to their expansion, to such a value that most of the useful work has been obtained from them. It pays to open the exhaust valve early, so allowing the pressure of the gases in the cylinder to fall before the piston reaches B.D.C. In this way, when the piston rises, it has less work to do in pushing out the remainder of the burnt gases.

Lastly, the exhaust valve remains open for a few degrees after the piston has passed T.D.C. and so both valves are open together for a short time. The angular movement of the crankshaft during which this occurs is called *valve overlap*. The object of overlap is to allow the outgoing gases to create a partial vacuum, by virtue of their inertia, so that the incoming gases may enter more freely.

The point made in (1) applies to each stage. A partly open valve greatly impedes the flow of the gases in or out, and since they must not be opened or closed too quickly, because of the excessive strain that would be imposed on the valve mechanism, they must start opening early and finish closing late on induction and exhaust strokes.

The table on p. 110 shows the timing of some of the better-known aero-engines.

It will be noticed that the timing of different engines varies considerably. It may be generally stated that the higher the speed at which the crankshaft revolves, and the faster the piston moves, the greater the lag or lead of the inlet and exhaust valves, and the earlier does the spark occur before top dead centre.

It might at first be thought surprising that the closing of the inlet valve is so long delayed, and the exhaust valve allowed to open so many degrees before the crankshaft reaches the extreme limits of its throw. It must, however, be remembered that angular movement

	Inlet Valve	Spark Advance	Exhaust Valve
Gypsy Major Series 1	Opens 20° early Closes 71° late	30°	Opens 62° early Closes 29° late
Cheetah	Opens 15° early Closes 75° late	28°	Opens 70° early Closes 20° late
Merlin	Opens 31° early Closes 52° late	45°	Opens 72° early Closes 12½° late
Sabre 11A	Opens 40° early Closes 65° late	22°–35°	Opens 65° early Closes 40° late
Wright Cyclone	Opens 15° early Closes 44° late	20°	Opens 74° early Closes 25° late
Bristol Pegasus	Opens 29° early Closes 47° late	29°	Opens 76° early Closes 40° late

of the crankshaft is not directly proportional to the distance the piston is moved in the same time. A movement of 45° on either side of B.D.C. will cause only a small corresponding linear movement of the piston, whilst the 45° on either side of a line drawn through the crankshaft at right angles to the line joining T.D.C. to B.D.C. is responsible for most of the piston movement along the cylinder.

The exact timing of an internal-combustion engine is extremely important, for it has considerable influence on the power that it can deliver.

Valve Mechanism.

A reference to fig. 2 shows how the inlet and exhaust valves in each cylinder are pushed forward to open the ports at the right time. The rim of each valve is held snugly against its seating by two or three *helical springs*. Some larger engines, of which the Merlin series is one example, employ two valves of each type in each cylinder to facilitate the entry and exit of the gases. The valve is opened by the movement of a hinged lever called the *rocker arm*, which depresses the valve against the restoring force of the springs. The other end of the rocker arm is lifted by the rotation of cams. In the in-line type of engine the cams for all the cylinders are carried on one shaft, and this *camshaft* is geared to the crankshaft in such a way that one makes only one revolution for two revolutions of the other. This ratio of camshaft to mainshaft speed is, of course, necessary in the four-stroke engine in order that each valve may open and close once during two complete revolutions of the crankshaft. The position of the camshaft determines the method of linking them to the rocker arms. In some in-line

engines it is housed in the crankcase close to the mainshaft. The rocker arms are then reached through *push rods*. This method is the one illustrated in fig. 2. With larger engines, especially when four valves are fitted in each cylinder, it is more convenient to place the camshaft along the row of cylinder heads in such a way that the cams bear directly on the ends of the rocker arms themselves. If this method is adopted, special means must be used to lubricate the camshaft.

A slightly different form of this valve-operating mechanism is to be found on radial engines. Valves, valve springs, and push rods are similar to those of in-line engines, but the camshaft is replaced by a

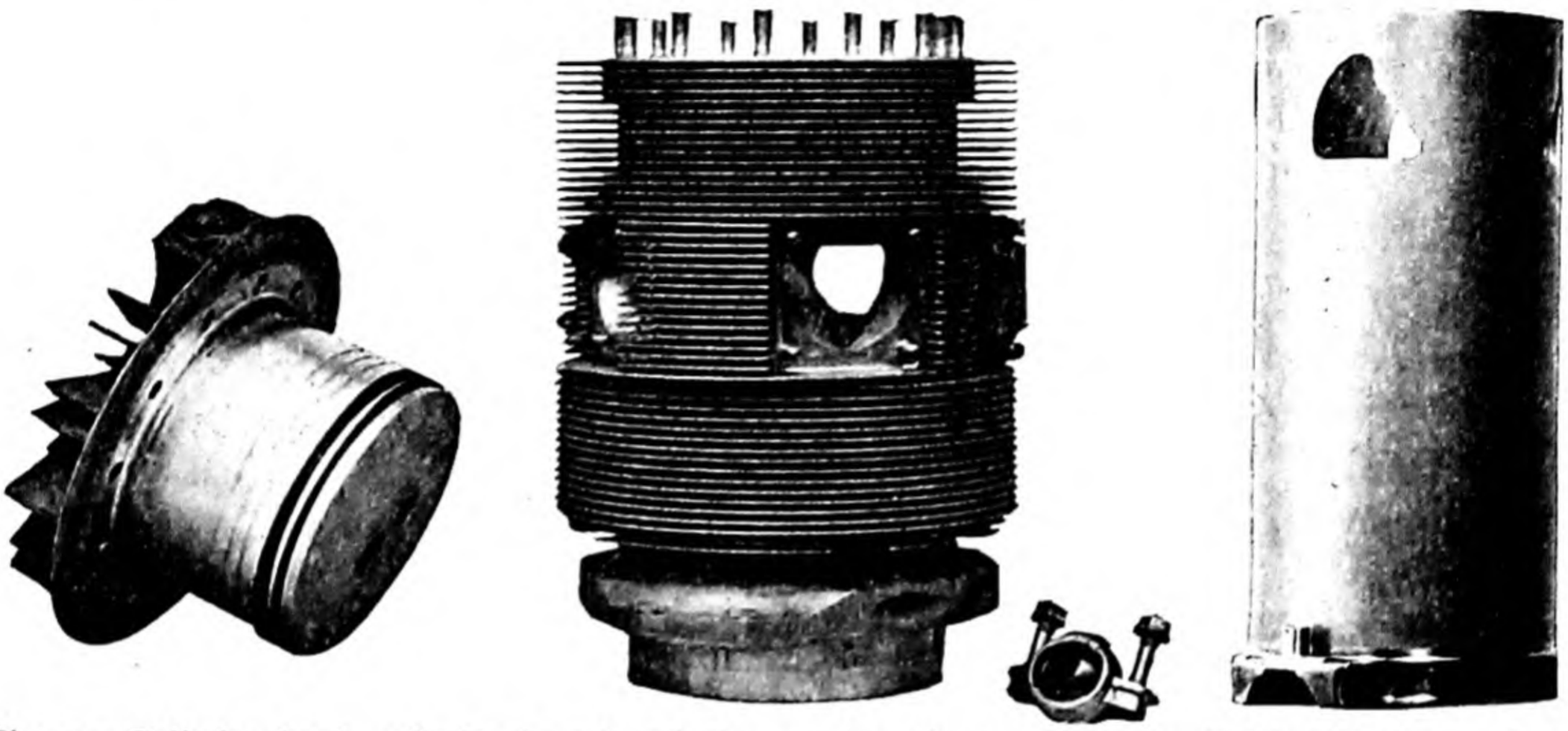


Fig. 7.—Cylinder head, cylinder barrel and sleeve valve of one of the *new* "Bristol" sleeve-valve engines

(By courtesy of the Bristol Aeroplane Co.)

cam-drum. This drum is carried in front of the engine, concentric with the mainshaft to which it is geared. The rim of this cam-drum is not perfectly circular, but carries, side by side, two rows of undulations or lobes which serve as lifting agents for the push rods that bear against them, one row working the inlet valves, and the other row the exhaust valves. The number of lobes in each row depends on the number of cylinders and on the direction of rotation of the drum. If the drum is so geared as to turn the same way as the crankshaft, the number of lobes per row is given by adding one to the number of cylinders and dividing the result by two. If the cam-drum rotates in a sense opposite to that of the crankshaft, the number of lobes is given by subtracting one from the number of cylinders before dividing by two. For example, the cam-drum and shaft in a seven-cylinder Cheetah radial engine turn the same way, and the number of lobes in each row on the cam-drum is four.

The type of valve described is called a *poppet valve*, and though most engines are so fitted, there is another way of providing openings into the cylinder which can be opened or closed. This is by the use of *sleeve valves* (figs. 7 and 8). The whole of the poppet-valve mechanism—valves, springs, rocker arms, push rods, and cam-drums—are

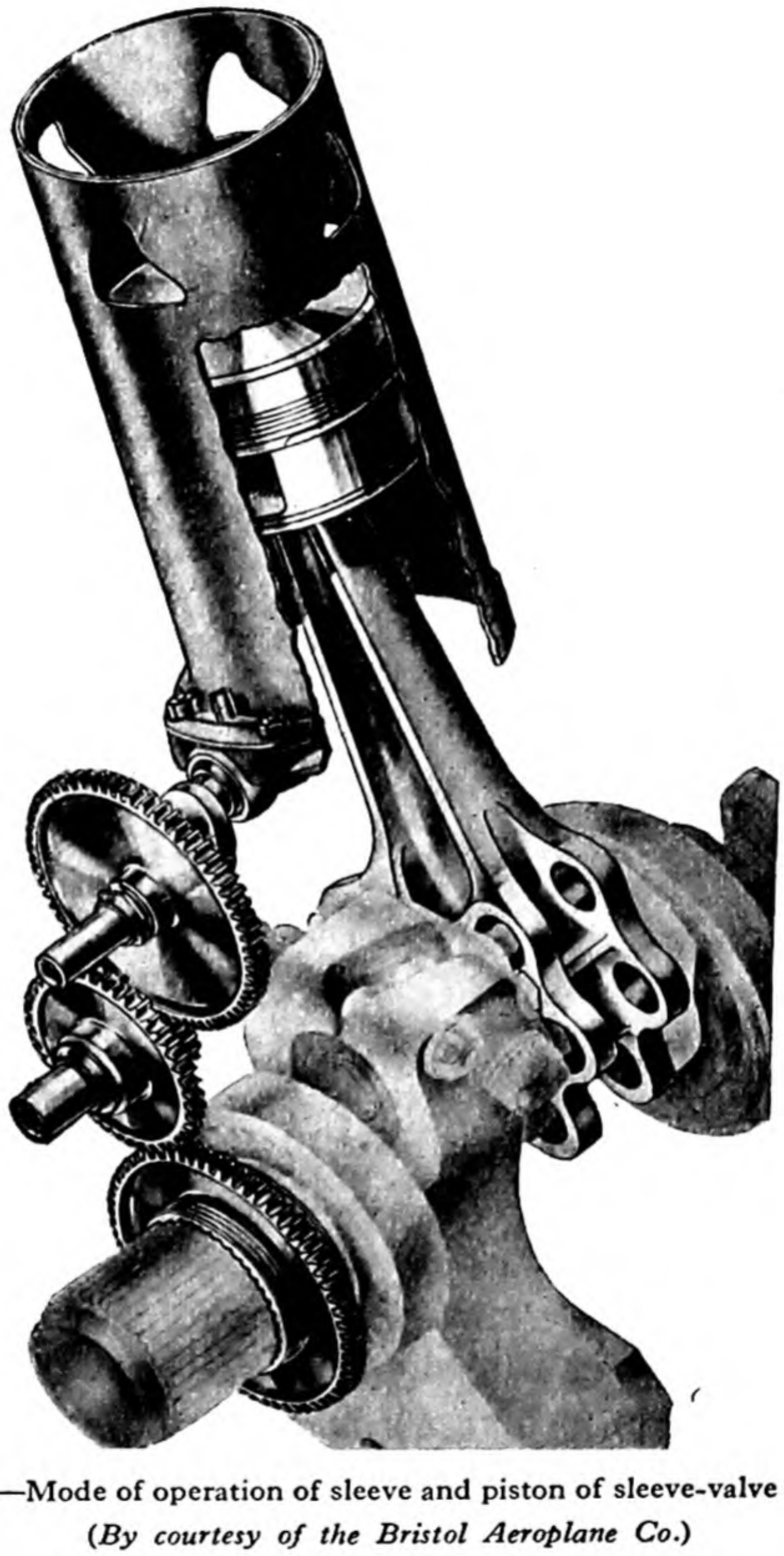


Fig. 8.—Mode of operation of sleeve and piston of sleeve-valve engine
(*By courtesy of the Bristol Aeroplane Co.*)

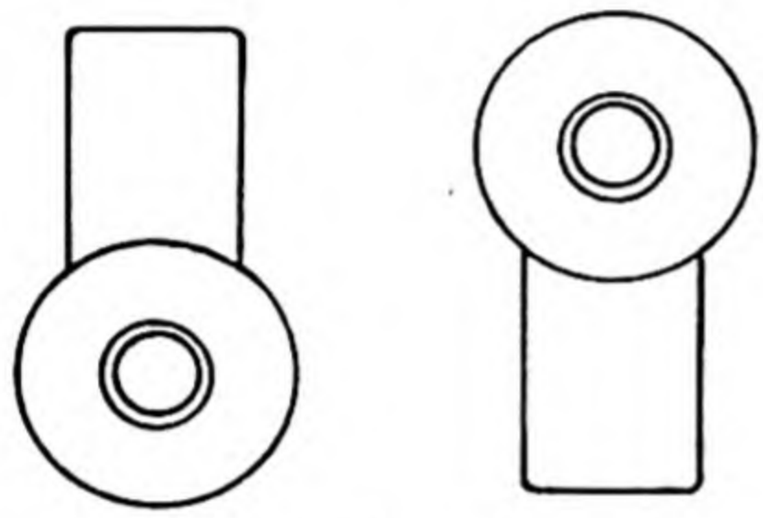
dispensed with, and their place is taken by a cylindrical sleeve sliding between the cylinder wall and the piston. Specially shaped holes in this sleeve are made to uncover at the right time inlet and exhaust ports in the side of the cylinder. The sleeve moves with a combination of reciprocating and rotary motion. The greatest advantage of the sleeve valve over the poppet valve lies in the reduction in the

number of components needed, with consequently increased reliability and reduction in the time necessary for maintenance.

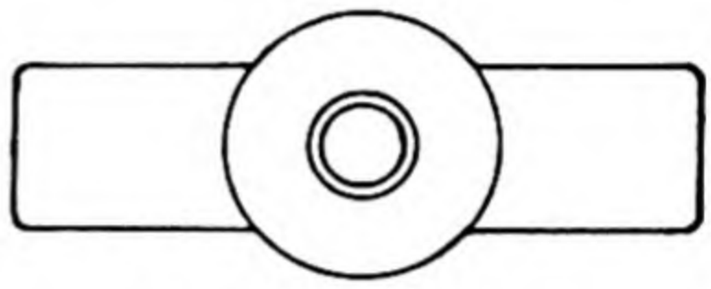
The Bristol Aeroplane Company have developed a series of radial engines of this type, of which the Hercules series of double-row, fourteen-cylinder radial engines is the most famous.

THE COMPLETE ENGINE

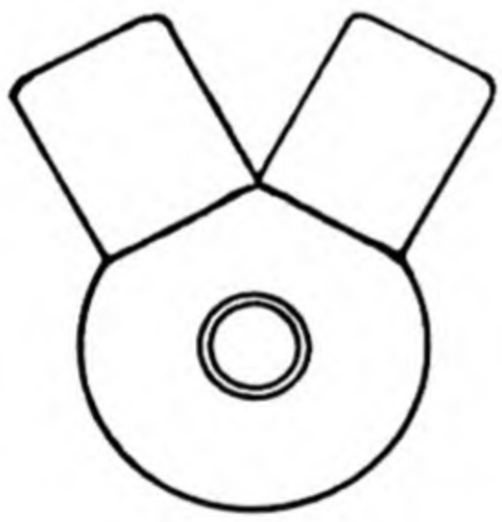
It will be convenient here to mention briefly the other essential parts of the complete four-stroke internal-combustion petrol engine. Each forms the subject of one of the following chapters.



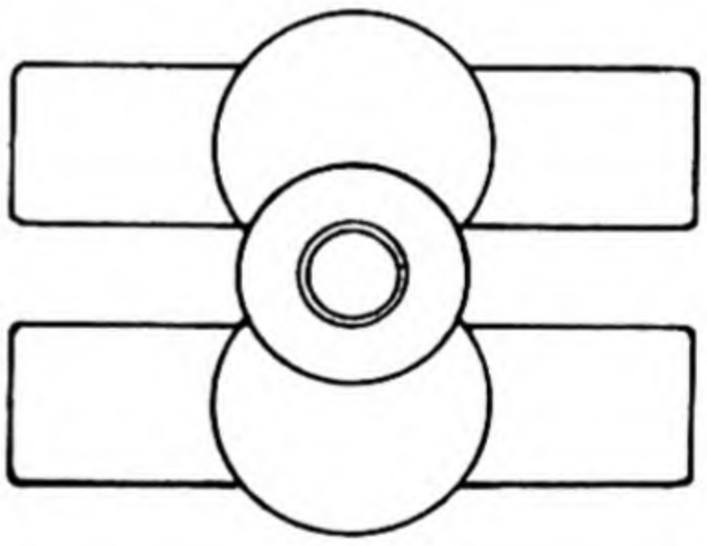
In-line: upright and inverted



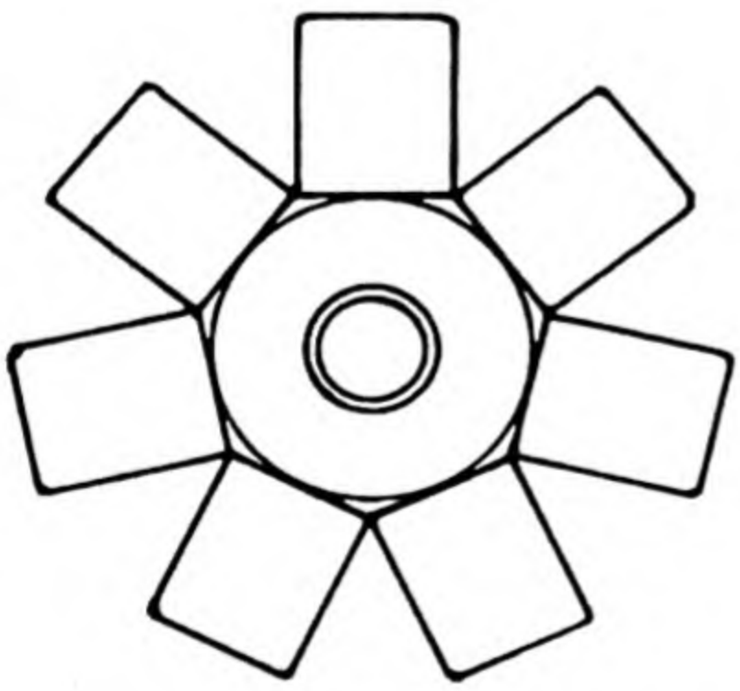
Horizontally opposed

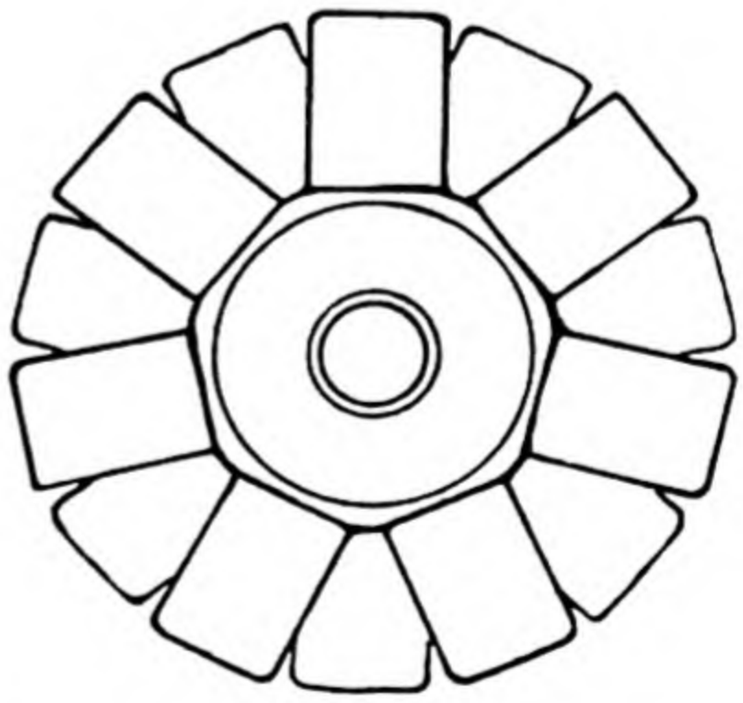


V-type



Horizontal H-type





Single-row 7-cylinder and double-row 7-cylinder radial

Fig. 9.—Cylinder arrangements

THE CARBURETTOR. The function of the carburettor is to measure out the fuel and air in the correct proportions, and to mix them in a finely divided state before they pass to the engine cylinders through the inlet manifold.

THE SUPERCHARGER. This is an essential component of all engines intended for efficient operation at high altitudes. It is a pump that ensures a sufficient weight of air being supplied to the engine even when that air is of low density or " thin ", as it is at great heights above the ground. Its pumping action also provides extra power at normal heights.

THE IGNITION SYSTEM. The spark that ignites the compressed mixture of petrol vapour and air in the cylinder takes place

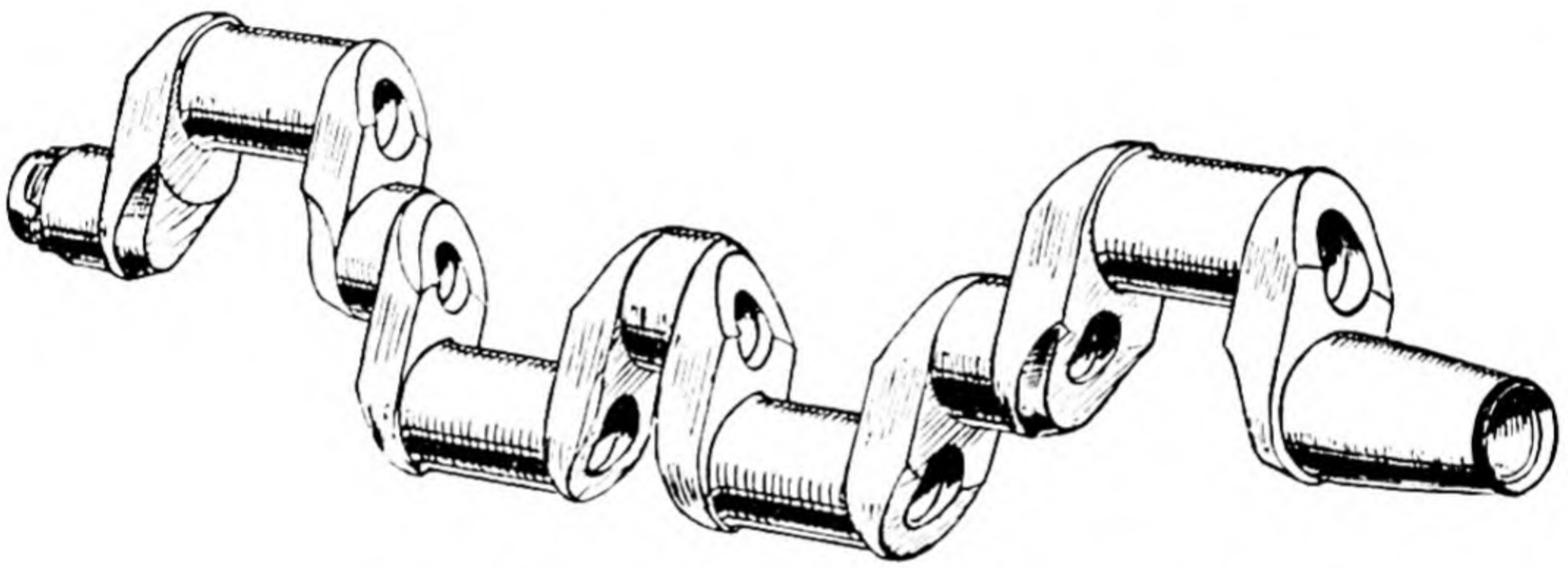


Fig. 10.—Crankshaft of a 4-cylinder in-line engine

across a small gap between the metal contacts of the *sparking plug.* The necessary high electrical voltage that causes this spark is supplied to the contacts by a special type of dynamo, and distributed to each plug at the proper moment. This dynamo and its distributing mechanism are designed as a single unit called the *magneto.*

THE LUBRICATION SYSTEM ensures that the engine shall run with the minimum of frictional losses, and in addition performs a number of other useful functions.

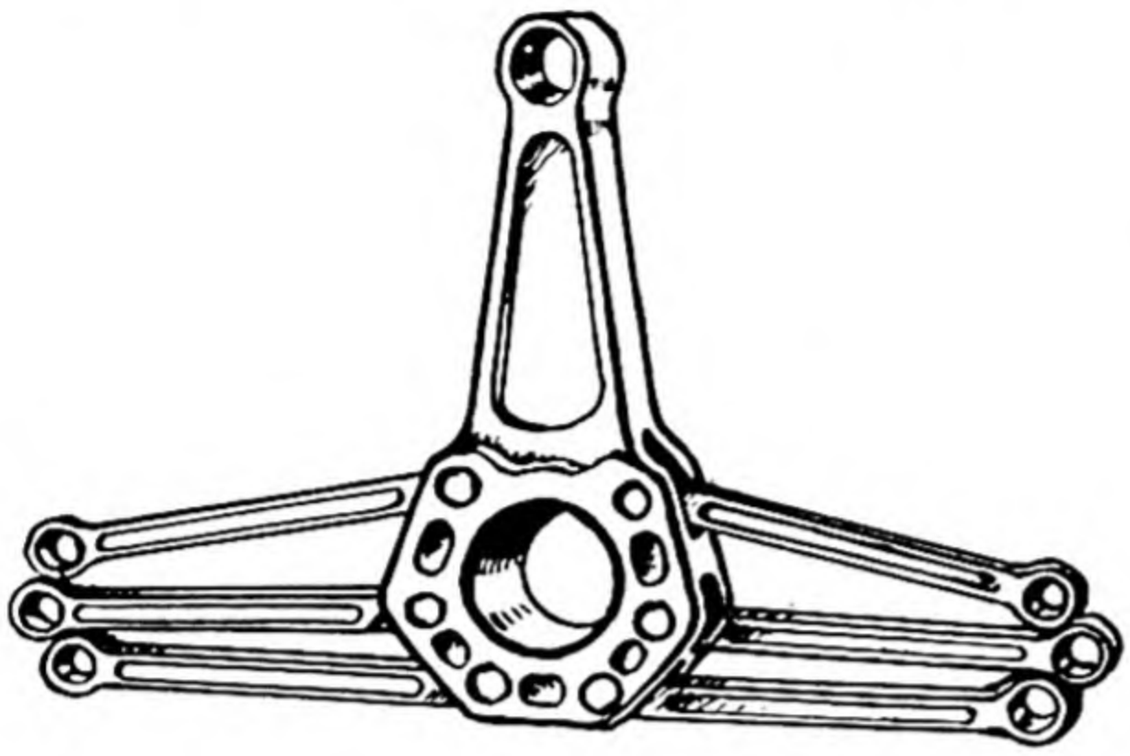
THE COOLING SYSTEM. The temperatures of the gases in the engine may rise to 2500° C., and it is evident that a great deal of heat will be transmitted to the engine parts in contact with them. A cooling system must be devised to carry away this heat.

Multi-cylinder Engines.

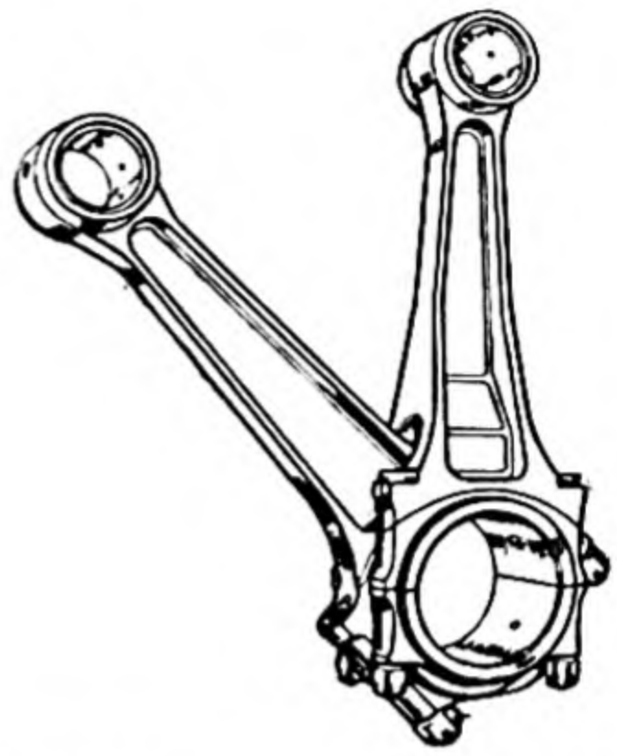
When explaining the principle of the four-stroke engine it was sufficient to consider a single cylinder, but a single-cylinder engine would not develop enough power for an aircraft. It would run roughly too, for the propeller would only receive an impulse from the crank-

shaft once in every two crankshaft revolutions. As many as twenty-four cylinders for one engine are in use at the present time.

There are two common ways of arranging these cylinders: in lines or banks, or radially like the spokes of a wheel. Some of the



Connecting rods of a radial engine showing master and articulated rods



A pair of connecting rods, comprising plain and forked components, from a V-type engine

Fig. 11

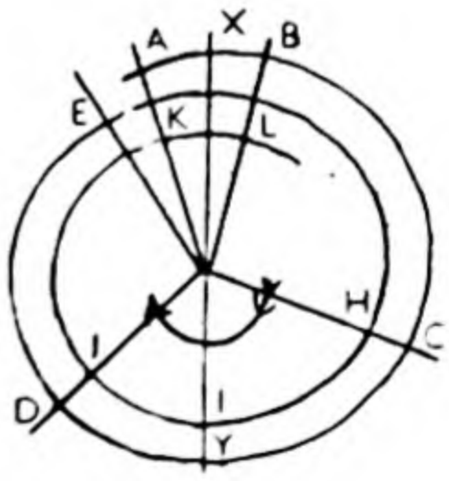
variations of the two types are shown in fig. 9. It will be noted that whilst the number of cylinders in a single bank of the *in-line engine* is always even, in a single row of the radial engine it is always odd (figs. 10, 11).

QUESTIONS

1. (*a*) What is the purpose of the compression piston rings?
(*b*) What is the purpose of the scraper piston rings?
(*c*) What purpose does the connecting rod serve?
(*d*) At what rate does the camshaft turn in the in-line engine?

2. Under the names of the four strokes as headings, tabulate the operations that are fulfilled, and the position of the valves in each stroke of the four-stroke cycle.

3. Here is a typical timing diagram of a four-stroke aero-engine. X is the Top Dead Centre, and Y is the Bottom Dead Centre. At X the piston is completing the exhaust stroke. Indicate by letter the following, writing your answers in a vertical column against the question numbers:



1. Where the spark occurs.
2. The exhaust stroke.
3. The stroke in which the gases are entering the cylinder.

4. The angular interval in which the pressure rise is most rapid.
5. The angular interval known as valve overlap.
6. The power stroke.
7. Where the intake valve opens.
8. Where it closes.

4. (*a*) Why does the intake valve close late, i.e. after B.D.C.?

(*b*) Why does the exhaust valve open early?

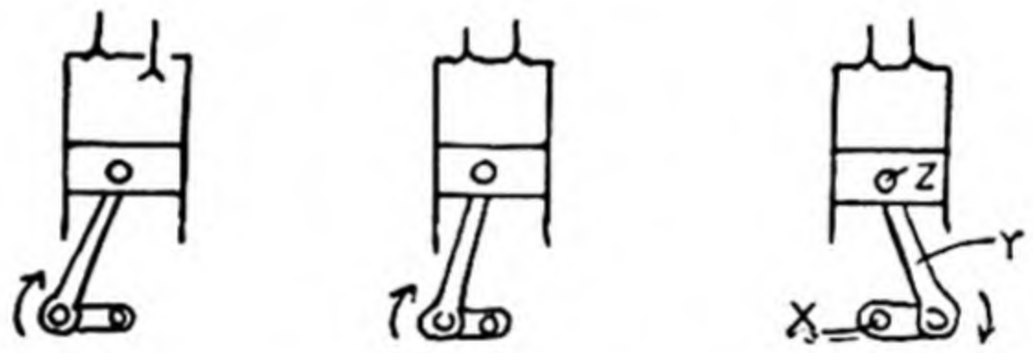
(*c*) What is the purpose of the valve overlap?

(*d*) Why does the spark occur approximately 25° before T.D.C.?

5. (*a*) Define (1) bore, (2) throw.

(*b*) What is the purpose of the connecting rod?

(*c*) How many revolutions does the camshaft make during ten revolutions of the crankshaft, and how many working strokes are there in this time with a four-cylinder engine?



6. The diagrams show a cylinder of an aero-engine in three different positions.

(*a*) What part of the four-stroke cycle is represented by the first diagram?
(*b*) What part of the cycle is represented by the second diagram?
(*c*) What part of the cycle is represented by the third diagram?
(*d*) Name, in order, the parts labelled *x*, *y*, and *z*.

CHAPTER X

How the Engine uses Heat

CALORIFIC VALUE. WORK, POWER, HEAT AND WORK. COMPRESSION RATIO AND ITS INFLUENCE ON THERMAL EFFICIENCY. DETONATION. OCTANE RATING.

The efficiency of an internal-combustion engine, or, indeed, of any heat engine, may be judged by the amount of useful work obtained from it for the consumption of a given quantity of the fuel it uses. Fuel, especially high-octane aviation spirit, is expensive, and the most efficient engine is that which can make the best use of it. Luckily the other essential part of the complete mixture burnt in the engine, namely the air, is free, so long as the engine continues to operate within the layer of atmosphere that lies on the earth's surface: though even in this case some payment must be made in the form of the work used to drive the supercharger, in order to pump sufficient air into the engine.

The amount of fuel used by an engine may be assessed in terms of expense: this is important. It may also be considered in terms of weight, for with an aircraft the reduction of the weight of fuel that must be carried is also of prime importance. A third way is to measure the actual heat content of the fuel, and to see what use the engine makes of it, and it is this aspect of the matter that is treated in the following paragraphs.

Calorific Value.

Chemists have discovered by experiment exactly how much heat is obtainable from 1 lb. of petrol when it is completely burnt by using an excess of air. According to the grade of petrol, the amount varies between 14,000 and 20,000 British Thermal Units. A British Thermal Unit (B.Th.U.) is the quantity of heat required to raise the temperature of 1 lb. of water by 1° Fahrenheit. Thus 1 lb. of a particular grade of fuel that liberates heat when burnt at the rate of 19,800 B.Th.U. per lb. could raise the temperature of 19,800 lb. of water through 1° F., or 1980 lb. of water through 10° F., or 132 lb. of water through 150° F., which in this last case would raise it to about its boiling-point. This 19,800 B.Th.U. per lb. is known as the calorific value, or heat value, of the particular fuel. It is the

scientists' way of measuring the value of fuel when used in an engine.

A large aircraft engine may use petrol at the rate of 10 lb. per minute. If the petrol has a calorific value of 19,800 B.Th.U. per lb., this rate is equivalent to the production of 198,000 B.Th.U. per minute. What happens to all this heat, sufficient to boil some 1320 lb. of water every minute?

When an engine is running at full throttle not all the petrol is

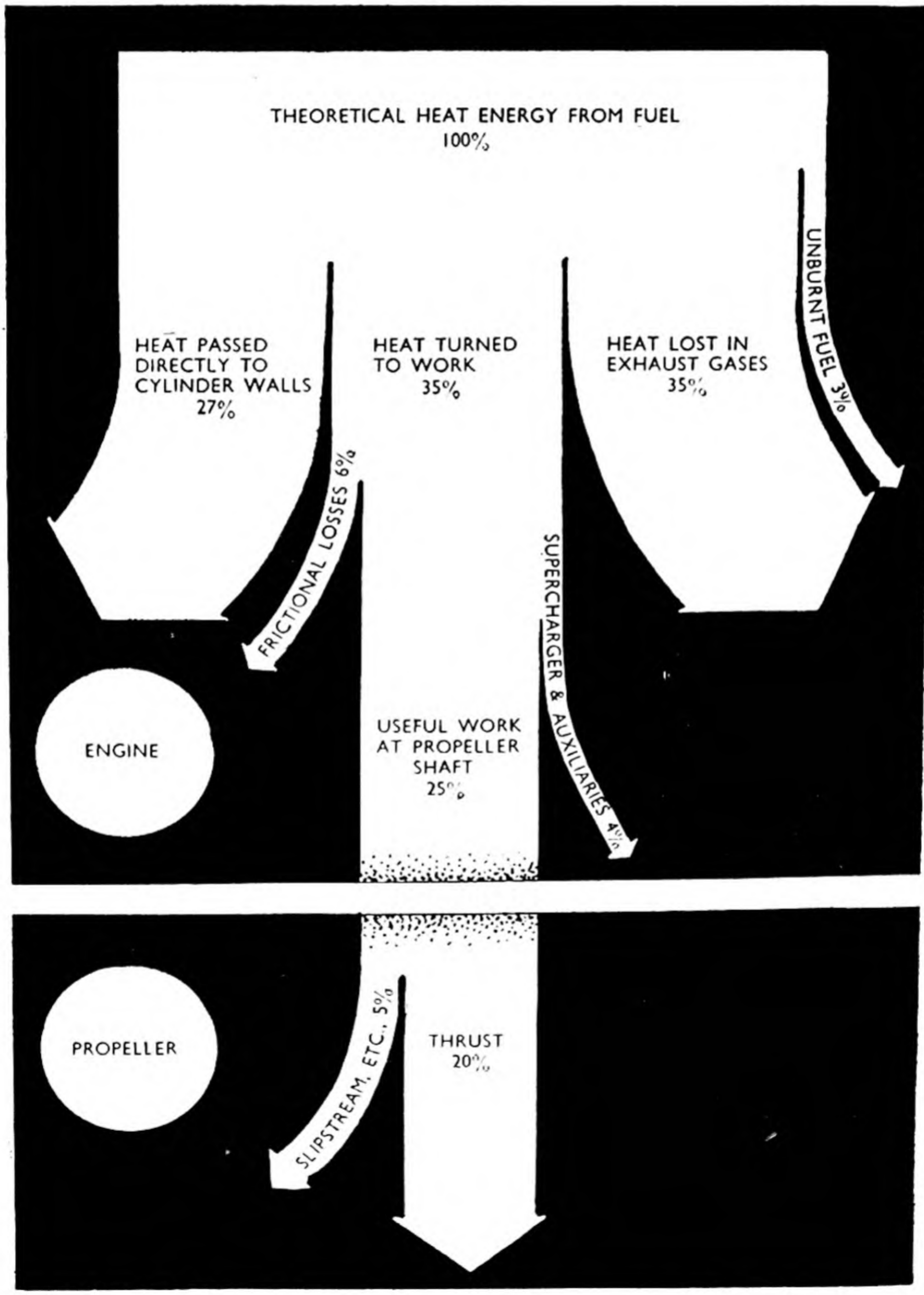


Fig. 12

burnt, so that some of it never even releases heat in the first place.

Of the energy produced by the rest, a very large proportion remains in the form of heat. Part of this heat passes directly to the cylinder walls and pistons, and is carried away by the cooling system designed to deal with it (p. 180 *et seq.*).

A still larger proportion remains in the gaseous products of combustion and in the unburnt, but heated, nitrogen in the air that enters the cylinders. This leaves with the exhaust gases through the exhaust manifold.

It is only the remainder, about a third of the total theoretical heat input, that is turned to work, and of this not all succeeds in reaching the propeller shaft. A small percentage is used up by friction in the bearings between the pistons and cylinder walls; this turns back to heat again and joins the heat removed by the cooling system and the circulating oil. Another fraction is used to drive the supercharger, if one is fitted, and auxiliaries such as magnetos, oil pumps, and fuel pumps, that are incorporated in the engine itself.

Eventually something like 25 per cent to 30 per cent of the originally computed heat content of the fuel reaches the propeller shaft to do useful work. This percentage is known as the Thermal Efficiency (or Heat Efficiency) of the engine. Strictly speaking, a distinction must be made between Indicated Thermal Efficiency and Brake Thermal Efficiency, according to whether the output considered is the total output of the cylinders, or that delivered at the propeller shaft. In either case the definition may be stated:

$$\text{Thermal Efficiency} = \frac{\text{Output in work}}{\text{Input in heat}} \times 100 \text{ per cent},$$

the quantities in the expression being measured either both in heat units or both in work units.

Fig. 12 shows the various ways in which the energy is used in the modern aero-engine. The figures are approximate, and the main purpose of the diagram is to indicate how the energy is expended. The propeller has been added to complete the story, and it will be noticed that the propeller, considered as a machine for changing engine torque into forward thrust, is about 80 per cent efficient.

Work.

The actual amount of work that an engine can deliver may be measured in units called foot-pounds (ft.-lb.). Suppose an engine were made to haul up a 1-lb. weight by means of a rope wound round a drum on the propeller shaft, and suppose that this 1-lb. weight

were lifted vertically through 1 ft.; then the engine would have done 1 ft.-lb. of work. If 5 lb. were lifted 20 ft., 100 ft.-lb. of work would have been done. It is in some such way that the output of an engine is measured, though the arrangement of a weight and a rope is hardly suitable for an aero-engine turning at high speed.

Power.

By means of a block and tackle or a system of levers, a child or small engine can do as much work as a man or large engine, though a longer time would be necessary for the process. For a true comparison of output, time must be taken into consideration, and the *rate* of doing work measured. The term *power* is used to denote the work done in unit time, or rate of doing work.

A small aero-engine might be capable of delivering power at the rate of 3,000,000 ft.-lb. per minute, whilst a larger engine might have a power ten times this value. These are cumbersome numbers, and it is found convenient to use a larger unit called the *horse-power*. It was when trying to sell his engines to men accustomed to assess work in terms of what a horse could do, that James Watt, inventor and early pioneer of steam-engines, found it useful to compare the output of his engines with that of horses. He used the term *horse-power to denote a rate of doing work of* 33,000 *ft.-lb. per minute*. He gave his customers good value, for only the strongest horse is capable of such an output, and then only for a short time. However, the term has remained in use, though it has very little relation to the power developed by a horse. A man can develop only about 1/10th of a horse-power for any extended period of time.

The horse-power of an engine running under certain stated conditions has, therefore, a precise meaning. It is a measure of the rate at which the engine is working. An engine of 1500 h.p. will do work, under the conditions assumed when stating this figure, at the rate of 1500 × 33,000 ft.-lb. per minute. The horse-power of an engine is not usually measured by the rate at which it can haul up a heavy weight. In the laboratory or in the testing sheds, the engine is made to work against the retarding force of a hydraulic brake. From the use of this arrangement comes the term "brake horse-power", which is a measure of the useful power output at the propeller shaft.

Heat and Work.

It has long been known that heat may be turned to work and work to heat, and that a given quantity of heat is equivalent to a certain fixed quantity of work. In other words, heat and work are theoreti-

cally interchangeable, and bear a fixed relation to one another. The results of experiment have fixed the " rate of exchange " at 778 ft.-lb. per B.Th.U.

Behind this lies one of the fundamental concepts of science, the indestructability of energy in its various forms, and the interchangeability of one form with another. For heat and work are both energy in different forms. The first is known as heat energy; the second, mechanical energy, is measured by the work it does. The change from heat into work, or work into heat, is a change in the form of energy, as an actor might doff one disguise to assume another. Energy has other disguises: it may appear as electrical energy, as chemical energy, or even as the energy of radiated waves. It is always possible to change one form into another. To take an example: the chemical energy in coal may be released as heat to drive the turbines of an electrical generator, and thus be changed first to heat, then to mechanical energy in the turbine, and finally to electrical energy by the generator. A housewife in a house fed by this generator may connect a vacuum cleaner, or an electric fire, to the electric supply, and so change electrical energy back to mechanical or to heat energy. Many other instances may be brought to mind. Without labouring the point, energy takes many forms, but is never created or destroyed. This is what enables an exact balance-sheet for the aero-engine to be drawn up, accounting for all the energy that goes into it.

Energy is like money, in that it is the exchange medium in the scientific world. We may have our wealth in dollars or pounds sterling, and there must be a definite rate of exchange between them. So too there must be a rate of exchange between the forms of energy. £1 is equivalent at the present time to 4.43 dollars, and 1 B.Th.U. is the equal of 778 ft.-lb., but there is this difference: in the latter case the rate never varies.

If a numerical value is to be found for the Thermal Efficiency of an engine, it is necessary to measure both input and output energy in one unit, and turn, say, the heat energy theoretically available from the combustion of the fuel into ft.-lb. This can be done by multiplying the number of B.Th.U.s of the input by 778.

In the same way, if it were necessary to compare the cost of a manufactured article with the cost of the raw materials from which it was made, and if the raw materials had been bought in dollars but the finished article were to be sold in England at a price fixed in pounds sterling, then it would obviously first be necessary to turn the dollar value of the raw materials to English money, or vice versa, using the rate of exchange between them.

An actual example will make this clear. Taking the figures already used, suppose that an aircraft engine, under certain conditions, consumes fuel of calorific value 19,800 B.Th.U. per lb. at the rate of 10 lb. per minute, and delivers 1500 h.p. The thermal efficiency of the engine may be computed as follows:

$$\begin{aligned}\text{Input} &= 19{,}800 \times 10 \text{ B.Th.U. per minute} \\ &= 19{,}800 \times 10 \times 778 \text{ ft.-lb. per minute.} \\ \text{Output} &= 1500 \times 33{,}000 \text{ ft.-lb. per minute.}\end{aligned}$$

$$\begin{aligned}\text{Thermal efficiency} &= \frac{\text{Output}}{\text{Input}} \times 100 \text{ per cent} \\ &= \frac{1500 \times 33{,}000}{19{,}800 \times 10 \times 778} \times 100 \text{ per cent} \\ &= 32 \text{ per cent.}\end{aligned}$$

Such an engine would be considered highly efficient for a practical internal-combustion engine using petrol.

Compression Ratio and its Influence on Thermal Efficiency.

When the piston is at T.D.C. there is still a small volume, called the *clearance volume*, left at the end of the cylinder, into which the

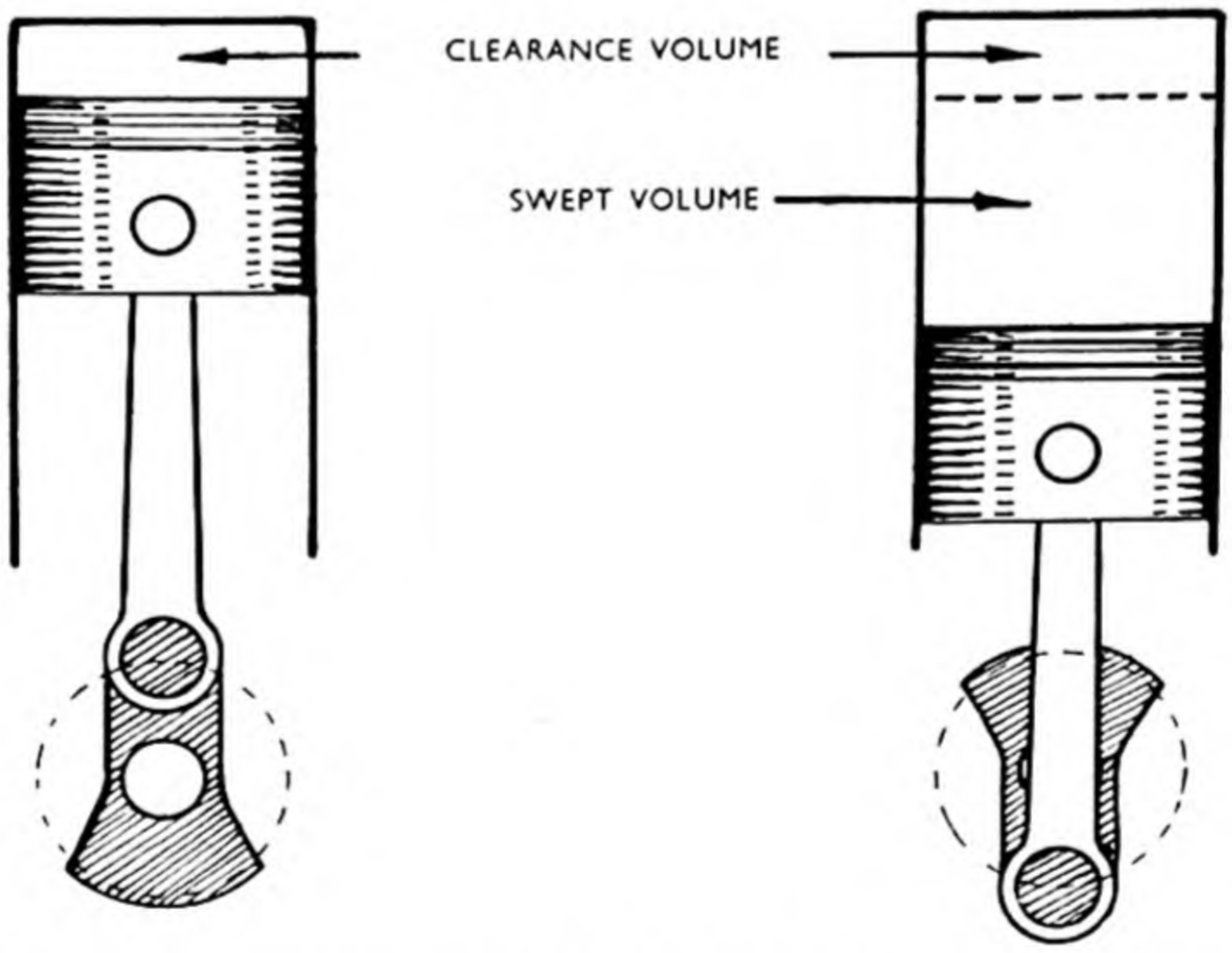


Fig. 13.—" Compression ratio is the ratio of the largest volume of the combustion chamber to the smallest "

mixture is compressed before the spark ignites it. The ratio of the largest volume of the combustion chamber (when the piston is at B.D.C.) to the smallest (clearance) volume is called the *compression ratio*. The volume swept out in the cylinder as the piston moves

from T.D.C. to B.D.C. is called the *swept volume*, so that compression ratio may also be defined as:

$$\frac{\text{Clearance volume} + \text{Swept volume}}{\text{Clearance volume}}.$$

It should be noted (see fig. 13) that this is a ratio of volumes, and not of pressures, though it gives an idea as to how much the gases are compressed. Aero-engine compression ratios vary from about $5\frac{1}{2}$ to $6\frac{1}{2}$.

It has been found that the compression ratio greatly influences the proportion of released heat that can be converted to work. The higher the compression ratio, the higher the thermal efficiency. This is understandable when it is realized that the smaller the clearance volume into which the gases are compressed before ignition, the higher will be the pressures when they are burnt.

We should like to design engines with higher and higher compression ratios so that we could turn more and more of the heat to work, but there is a limit to the compression ratios which can be used. This limit is reached when the engine begins to detonate.

DETONATION

The burning of the charge inside the combustion chamber is often referred to as an " explosion ", but this gives a wrong idea of what normally happens. If it were possible to watch the process in " slow motion ", the spark would be seen igniting that portion of the mixture surrounding it, and the resulting flame would be seen spreading evenly. A flame front, sharply defining the burning charge from that as yet unburnt, would be noticeable. The flame front would spread across the cylinder until all the mixture had been ignited. All this occurs in a very small fraction of a second, whilst the crank turns through about 30°. Nevertheless the charge has not exploded, but burnt smoothly, and the pressure on the piston crown has continuously increased until just after T.D.C., when all the charge has been burnt and the maximum pressure is reached.

Sometimes the burning may start in the normal manner, but if the temperature is too high, the remainder of the charge may suddenly " explode ". This is called *detonation*. The temperatures and pressures resulting from this explosion are far in excess of those produced by proper burning, and are produced when the piston is very near T.D.C., at a time when they do most harm and least good. For at T.D.C. the connecting rod and crank web are in line, and any im-

pulse on the piston may damage the big-end bearing without producing any turning effect.

The piston receives a violent blow instead of being pushed more or less evenly down the length of its stroke. It is as if we tried to propel a bicycle by hitting the pedals with a hammer when they were near the top, instead of pushing with our feet.

The likelihood of detonation can be reduced by a well-designed combustion space in the cylinder head, free from pockets in which excessive pressures may precipitate the explosion. Turbulence, arising from the mode of entry of the gases through the inlet port, will also reduce the possibility of detonation. A third factor tending to the same end is the use of two sparking plugs, enabling the flame front to start from two places at once in the cylinder. In a sleeve-valve engine, with no very hot exhaust valve and a good combustion-chamber design, the compression ratio may be raised beyond that possible with a similar type of poppet-valve engine.

Detonation will cause mechanical damage to the cylinder heads and big-end bearings and the piston crown may cave in. In addition, the excessive temperatures may give rise to burning and pitting of the valves and valve seats, and such troubles as sticking and seized piston rings may result. Compression ratios are pushed to the limit in modern aero-engines, and detonation may occur if the pilot does not handle his engine correctly. Although the results may not be noticeable at once, eventual engine failure will occur. Someone else may be taking off with the damaged engine when it fails.

The characteristic of detonation is the knocking or "pinging" that is caused by the hammerlike blow on the cylinder walls and piston, but this is not always heard in the general noise, especially if other engines are running. If there is a sudden drop in power, and a rise in the cylinder-head temperature, detonation should be suspected.

A pilot may cause detonation of his engine by using too weak a mixture or too high a boost, or by climbing at low airspeeds. These errors and other rough handling of his engine should be avoided. There are limits to what it will stand. Engine revolutions should not exceed the maximum permissible, and there is usually a red line on the tachometer (revolution counter) as a warning. After take-off the engine revolutions should be reduced as soon as possible.

Octane Rating.

The type of fuel used in an engine has considerable influence on the problem of detonation.

Different fuels differ considerably in their ability to resist detona-

tion. The normal petrol is a mixture of very many different hydrocarbons. In order to measure its anti-knock qualities, it is compared with a special petrol, which is a mixture of two hydrocarbons. One of these, called iso-octane, does not detonate readily. The other petrol in this special standard fuel is called heptane and detonates very easily.

To find the rating of any fuel a special engine is used, in which the compression ratio can be varied by screwing down the cylinder head into the cylinder barrel. This engine is fed with the fuel whose properties are to be investigated, and the compression ratio increased until detonation just begins. Leaving the engine in this condition, it is now run on the standard fuel of iso-octane and heptane, and the percentage of heptane is gradually increased until a mixture is obtained which produces detonation once again.

Suppose that there were then 80 parts by weight of iso-octane to 20 of heptane in the standard fuel, the other fuel would be rated as 80 octane fuel. To put it briefly, the term " 80 octane fuel " means that the fuel has the same anti-knock properties as a mixture of 80 parts of iso-octane to 20 parts of heptane by weight. If detonation is to be avoided, it is essential that the octane fuel used should be that for which the engine is designed and which is usually marked on the side of the aircraft. Nothing, however, is gained by using fuel of a higher octane rating than that specified for the engine: the only result is the waste of money.

QUESTIONS

1. (*a*) What is detonation?

(*b*) Define compression ratio.

(*c*) What is the influence of compression ratio on detonation?

2. (*a*) Name any one thing that might lead you to suspect that detonation was occurring in your engine.

(*b*) Mention any two effects of detonation on the engine parts.

(*c*) What is the effect on the engine of using 70 octane fuel in an engine for which the correct fuel is 80 octane?

(*d*) What would be the result of using 100 octane fuel in the same engine?

3. A small two-seater monoplane uses petrol at the rate of 1 lb. per minute, when the engine is developing 120 h.p. If the calorific value of the fuel is 18,000 B.Th.U. per lb., what is the thermal efficiency of the engine?

(Assume 778 ft.-lb. per B.Th.U. and 1 h.p. to equal 33,000 ft.-lb. per minute.)

4. At take-off the engine of Question 3 develops 150 h.p., but the efficiency falls off to 20 per cent. What is its rate of consumption of petrol in lb. per minute under these conditions?

CHAPTER XI

How the Engine Prepares its Food: the Carburettor

THE FUNCTION OF THE CARBURETTOR. THE SIMPLE CARBURETTOR. THROTTLE VALVE. THE AIRCRAFT CARBURETTOR. MIXTURE RATIO AND AIRFLOW THROUGH THE CHOKE TUBE. MIXTURE RATIO AT THROTTLE OPENINGS OTHER THAN NORMAL. ACCELLERATOR PUMP. EFFECT OF ALTITUDE ON CARBURATION. ICING. INJECTION CARBURETTORS. THE COMPLETE FUEL SUPPLY SYSTEM.

The Function of the Carburettor.

The carburettor is the kitchen where the food for the engine is prepared. Its two-fold purpose is:

1. To measure out the petrol and air in the correct proportion. This is called " metering " the fuel.
2. To mix these two thoroughly together in a finely divided state.

The air is drawn in through one, or sometimes two, wide tubes, called *choke tubes*, and the petrol is introduced into the airstream at this point through one or more outlets or nozzles in the form of a fine spray.

The choke tube and petrol outlets, together with the means of regulating the petrol supply to these outlets, are built as a unit: this is the carburettor.

The mixture is distributed to the cylinders by means of the inlet manifold, a wide branching tube that joins the choke tube to the inlet ports of the engine. It is not an easy matter to design the inlet manifold in such a way that each cylinder receives an equal share of properly proportioned mixture, and some care and thought go to finding the best shape for any particular engine. In small engines with four cylinders in line, such as the De Havilland Gypsy series, Blackburn Cirrus, and American Menasco engines, the mixture is taken to the centre of the manifold, which then branches to feed two cylinders on each side of the centrally placed inlet, as shown in fig. 14.

In larger engines the charge passes through the supercharger on its way to the inlet manifold. It is usual, in the case of radial engines

fitted with superchargers, to have inlet ducts evenly spaced around the annular tube into which the air is compressed at the periphery of the supercharger, and these tubes lead radially to the separate cylinders, as shown in fig. 15. This symmetrical arrangement helps to ensure a proper distribution of the mixture.

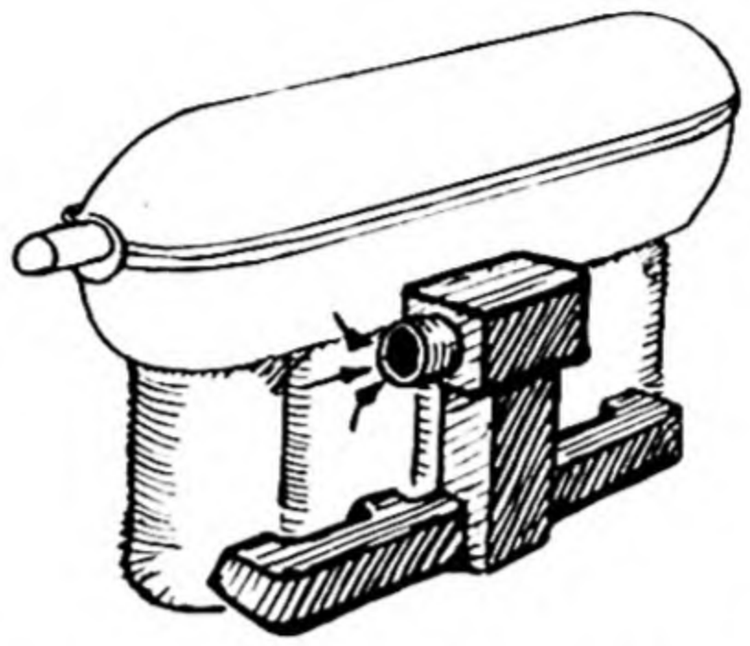


Fig. 14.—Carburettor and inlet manifold of small 4-cylinder in-line engine

By the time the charge is ignited in the cylinder all the petrol should normally be in the form of a vapour. Various factors contribute to the complete evaporation of the liquid fuel.

Firstly, the small droplets that are ejected from the petrol outlet present a very large surface area relative to the weight of the liquid.

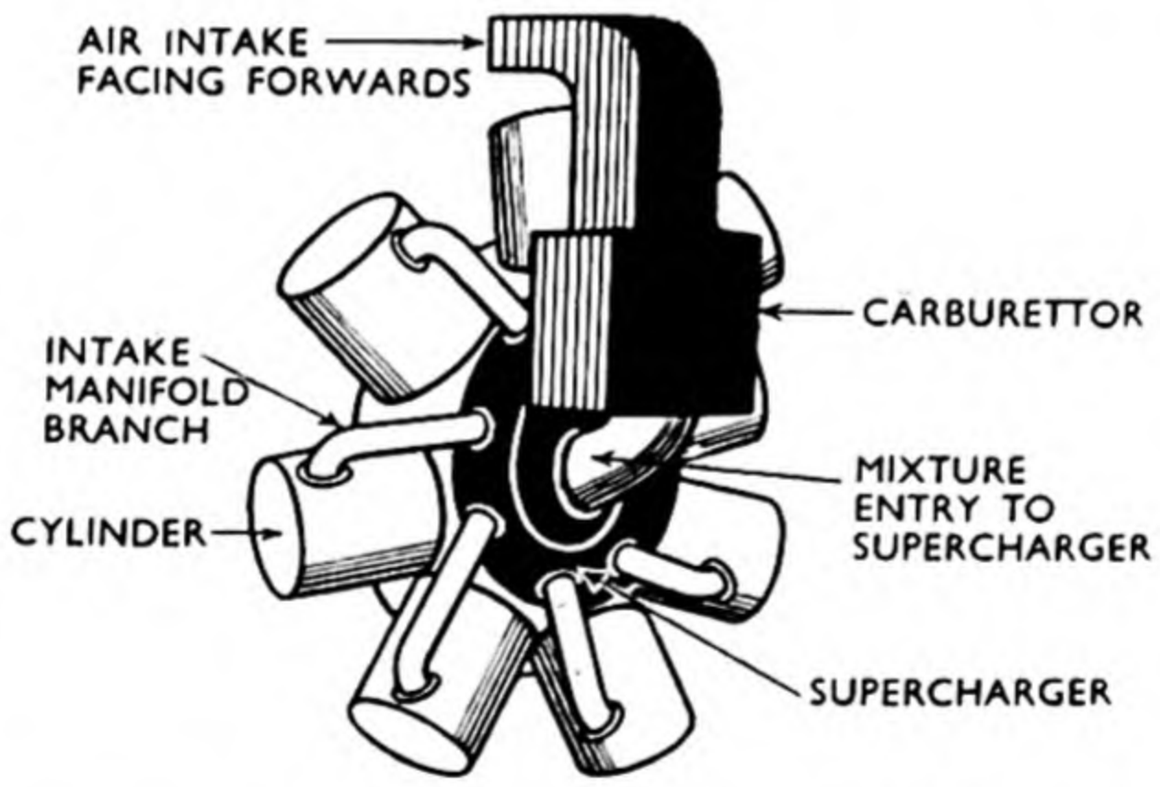


Fig. 15.—Arrangement of carburettor and inlet manifold of typical radial engine

Evaporation from such a large surface is rapid. The same thing is met with in scent sprays and insecticide sprays; the fine state of division of the liquid as it leaves the nozzle results in its almost immediate evaporation, so that no drops of liquid actually reach the ground.

A second factor that helps to evaporate the petrol is the turbulent nature of the airflow at various stages in its passage to the cylinders; first in passing the throttle valve, then as it is flung from the rotating

blades of the supercharger, and finally as it rushes through the space between the inlet valve and its valve seating with a velocity increased by the narrowness of the gap through which it must flow.

Lastly, the warmth of the inlet manifold, and, to a greater extent, that of the cylinder itself, completes the change from liquid to gaseous state. A certain amount of heat is generated by the compression in the supercharger, so that the mixture leaves the supercharger at a higher temperature than it entered; indeed it is sometimes necessary to cool the mixture at this stage. Mention must also be made of the fact that heat may be applied to some carburettors when the air entering the choke tube is cold, and one of the effects of such carburettor heating is to assist in the evaporation of the fuel.

During the induction stroke the gaseous pressure inside the cylinder drops below the atmospheric pressure at the mouth of the air intake of the carburettor. This pressure difference causes the flow of air. It might be said that the increasing volume in the cylinder as the piston moves down on the induction stroke, aided in the beginning by the momentum of the outgoing gases, creates a partial vacuum which the atmosphere attempts to fill. The engine is, in fact, pumping the air into the cylinders, and it is this pumping action that is mainly responsible for the airflow. Usually the air intake faces forward, and there is therefore a " ramming " effect due to the relative air velocity. This may give an increase in pressure, as the air is slowed down relative to the aircraft, equivalent at high speeds to another 2 lb. per square inch, about a seventh of an atmosphere. This contributes in faster aircraft to the weight of air entering the cylinders.

The Simple Carburettor.

The principle on which English aircraft engine carburettors operate is best grasped by examining first a simplified form of this type of carburettor, shown diagrammatically in fig. 16.

The fuel is fed from the fuel tank into a float chamber that works rather like a water cistern. Inside the float chamber, a float and needle valve keep the petrol at a constant level. This level is just below the mouth of the petrol outlet in the choke tube. Between the float chamber and the outlet is a brass plug with one or more small holes through it. This is the metering jet, whose purpose is to regulate the flow of fuel to the outlet.

In the simple carburettor the jet is usually situated at the petrol outlet in the choke tube, but, as will be seen later, it is often more convenient in aircraft carburettors to have the jet submerged in the petrol inside the float chamber.

The petrol outlet is situated at the narrowest part of a constriction or "neck" in the choke tube. This is smoothly shaped and the streamline flow of the air is preserved. Under these circumstances there is an increase in the speed of the flow in the narrowest part of

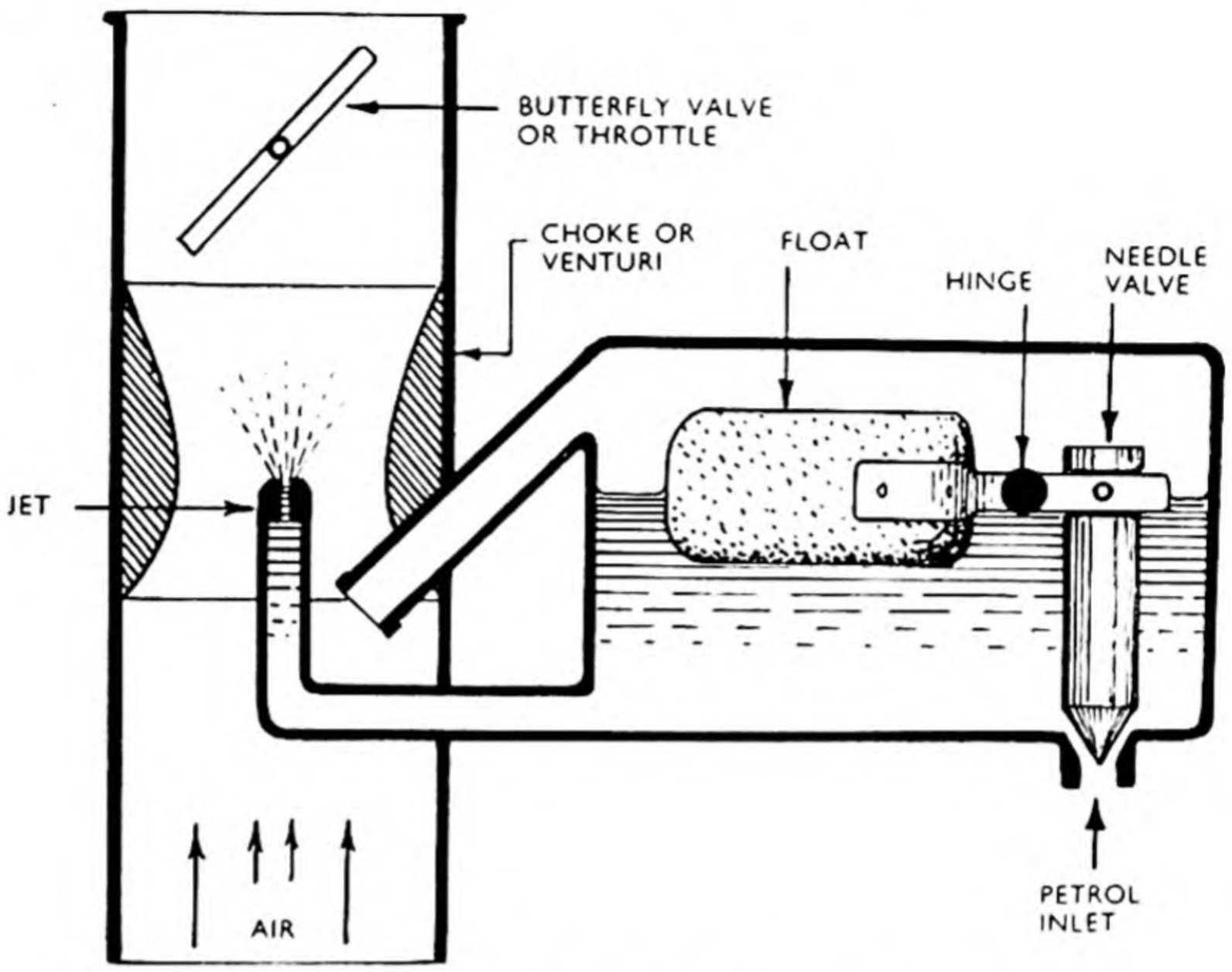


Fig. 16.—The simple carburettor

the constriction, and the extra kinetic energy is obtained at the expense of a drop in pressure. This is another example of the Venturi effect: occasion has arisen to refer to this physical principle before in connexion with the airflow round the aircraft's wings (p. 4).

Because of the drop in pressure in the choke, the fuel will be forced up the delivery tube under the excess of pressure existing between the surface of the fluid in the float chamber at normal pressure and the outlet in the choke waist.

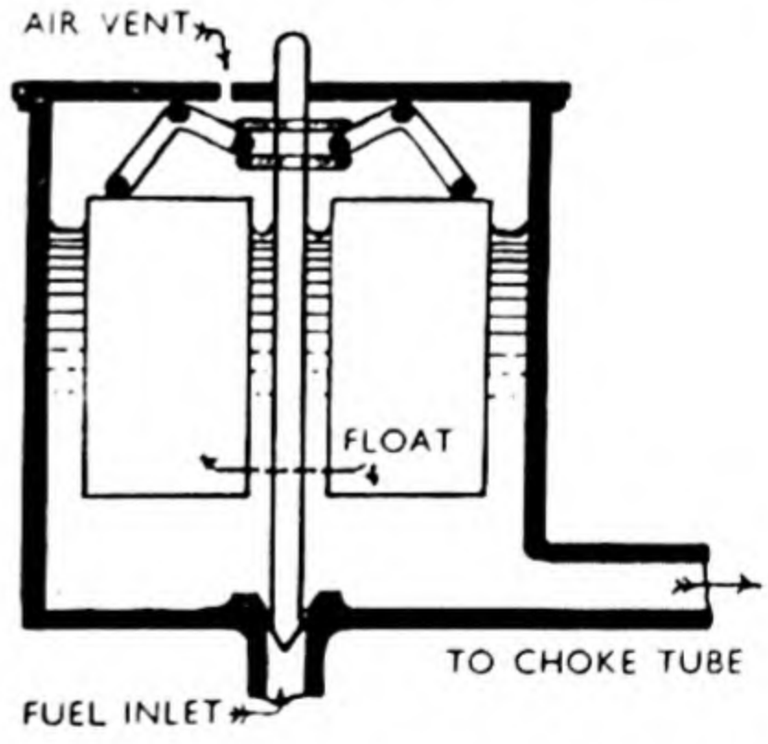


Fig. 17.—Automobile carburettor float chamber

It is sufficient in motor-car carburettors to vent the float chamber directly to the air through a small hole in the cover, as in fig. 17. This would be unsatisfactory in an aircraft: firstly, because fuel might be spilt during aerobatics, with risk of fire, and secondly, because of chance changes in pressure that might occur round the carburettor during manœuvres.

The float chamber of an aircraft carburettor is therefore sealed off, and the necessary pressure balance is obtained by leading a tube (the pressure-balance duct) from the float chamber to a point in the air intake just before the constriction. It is therefore the pressure difference that exists between the point where the mouth of this duct is situated and the narrow part of the choke where the petrol outlet is placed, that causes the flow of liquid fuel from the float chamber.

Throttle Valve.

If the power output of the engine is to be capable of variation to suit different conditions of flight, it is necessary to have some means of regulating the rate of flow of mixture into the cylinders. For this purpose a valve, referred to as the butterfly valve or throttle valve, is placed in the path of the incoming mixture just after it passes the choke tube. This consists of a disc, of circular or elliptical shape, hinged about a diameter in such a way that by rotating it the inlet may be partially or almost wholly blocked. This valve is directly linked to the pilot's throttle lever, which thus becomes the chief means whereby the pilot controls the engine output.

THE AIRCRAFT CARBURETTOR

The simple carburettor serves to illustrate the fundamental principles of carburation. Such a device works satisfactorily on a motor-car, but suffers from certain limitations that make it unsuitable, without modification, for an aircraft engine. These modifications will now be described, and the reason for their use given.

Mixture Ratio and Airflow through the Choke Tube.

The size of the holes through the jet can be adjusted to supply petrol-air mixture in any chosen proportion at one given throttle setting, but if the throttle is opened or closed, the simple carburettor fails to maintain this proportion. Thus, if the mixture ratio is correct at one given engine speed, then *it becomes richer as the throttle is opened and the engine speed increased.* The rates of flow of air and petrol are not directly proportional to one another, and when the airflow through the choke tube is increased, the flow of fuel increases at a greater rate and is drawn from the jet in too great a quantity. A typical discharge curve for a simple carburettor is shown in fig. 18, showing how the proportion of fuel to air increases as the throttle is opened.

The constant mixture strength that is required may be obtained in a number of ways, the chief being the Bavery method, used in Zenith carburettors, and the diffuser. The latter is in widespread use in one form or another, and is a feature of Claudel Hobson carburettors.

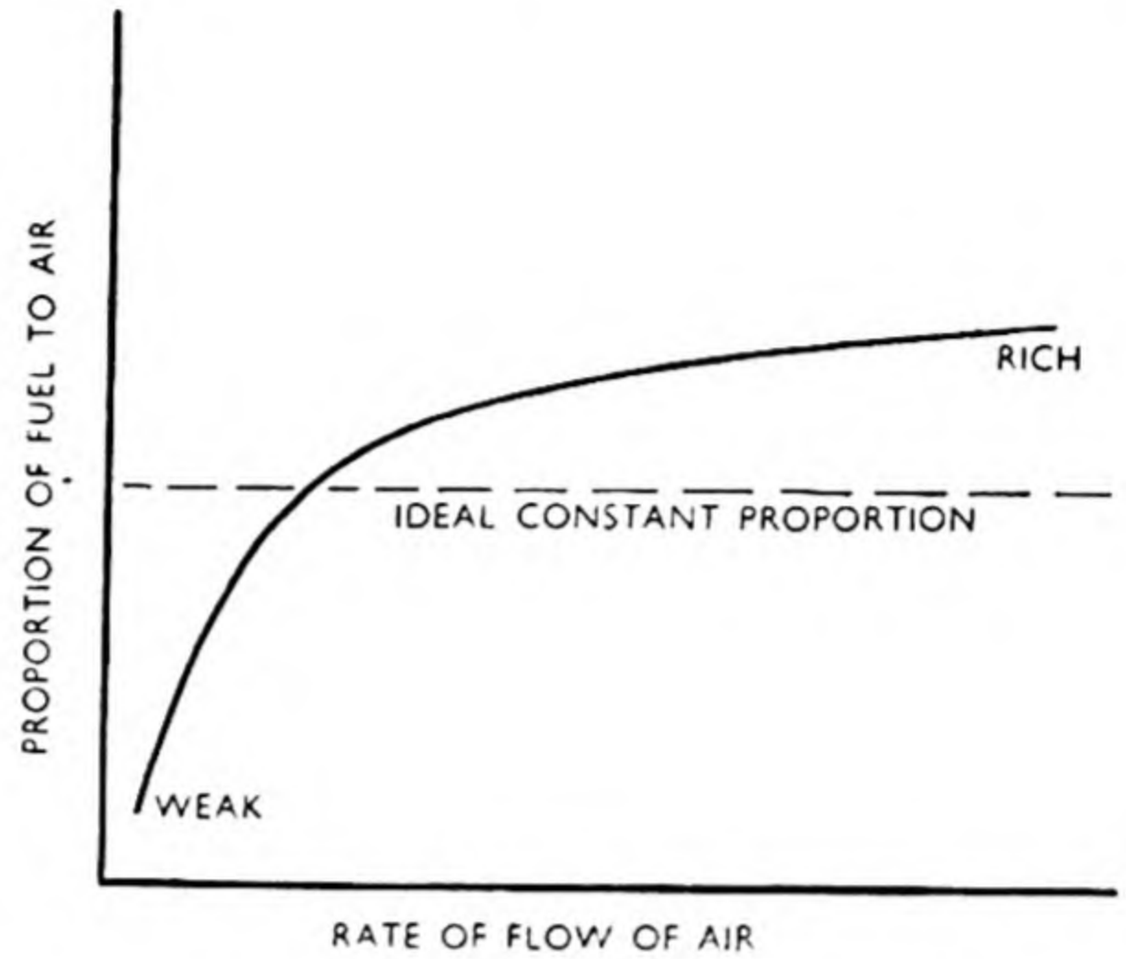


Fig. 18.—Discharge curve for simple jet

The Zenith system is shown diagrammatically in fig. 19. Two concentric outlets are used. The first is of normal design with the jet at the mouth of the outlet, and supplies a mixture too weak at small throttle settings, but becoming richer as the throttle is opened. The other jet is arranged to do just the opposite, giving a mixture richer when the throttle is closed than when open. The two together main-

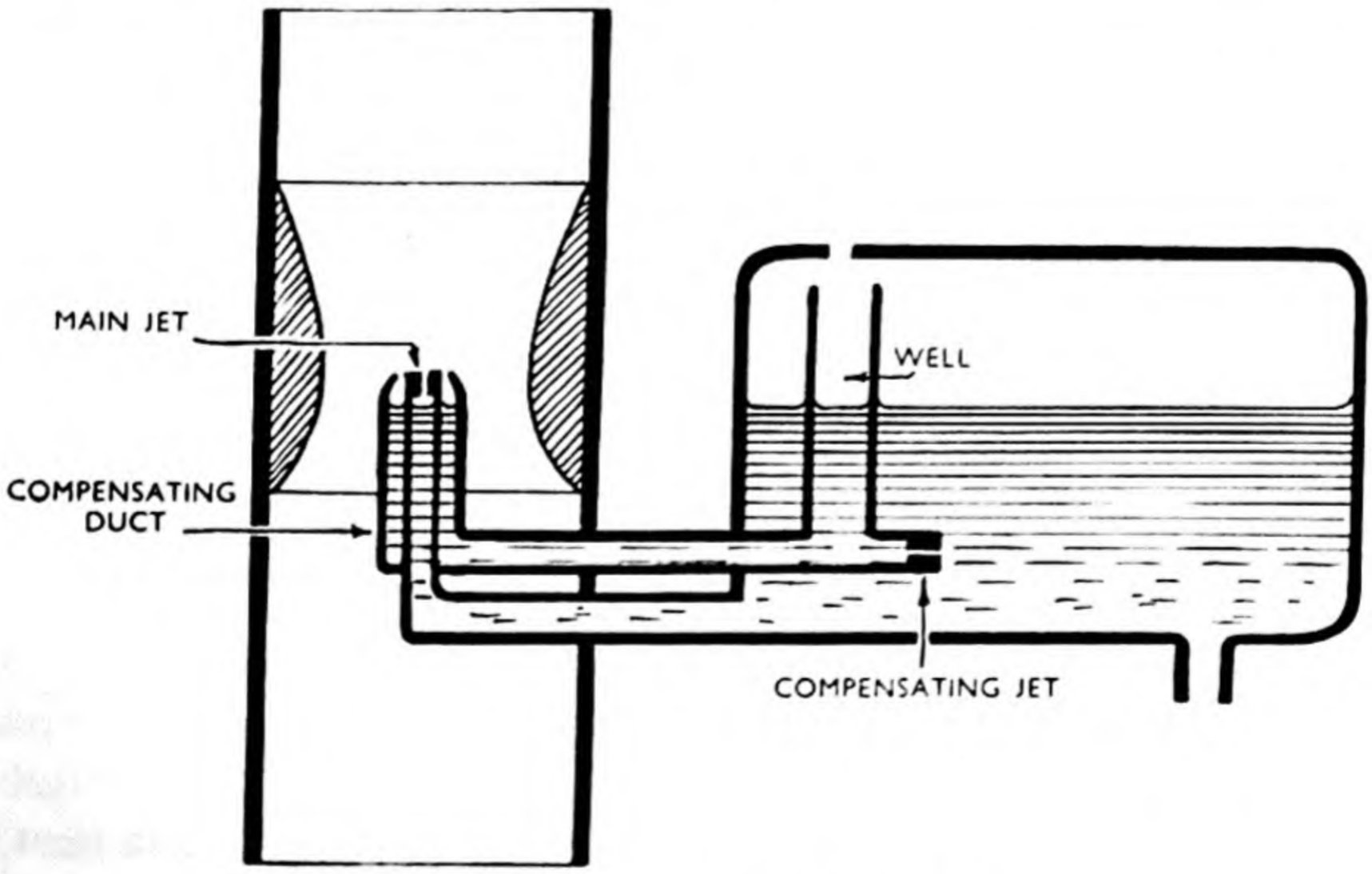


Fig. 19.—Zenith compensating system

tain a constant mixture strength. This second duct is connected to a well, open to the atmosphere, and deriving its fuel from the float chamber by way of a submerged jet of larger size than that in the normal outlet. At low engine speeds this jet delivers the larger part of the petrol drawn from the two ducts. At somewhat higher engine speeds the second outlet calls for a greater rate of flow than its jet is able to supply, and in consequence the liquid level in the well falls. A greater suction is therefore needed to lift the petrol in the second duct into the choke tube, and a smaller rate of flow results. At still higher engine speeds the well is completely emptied and some air

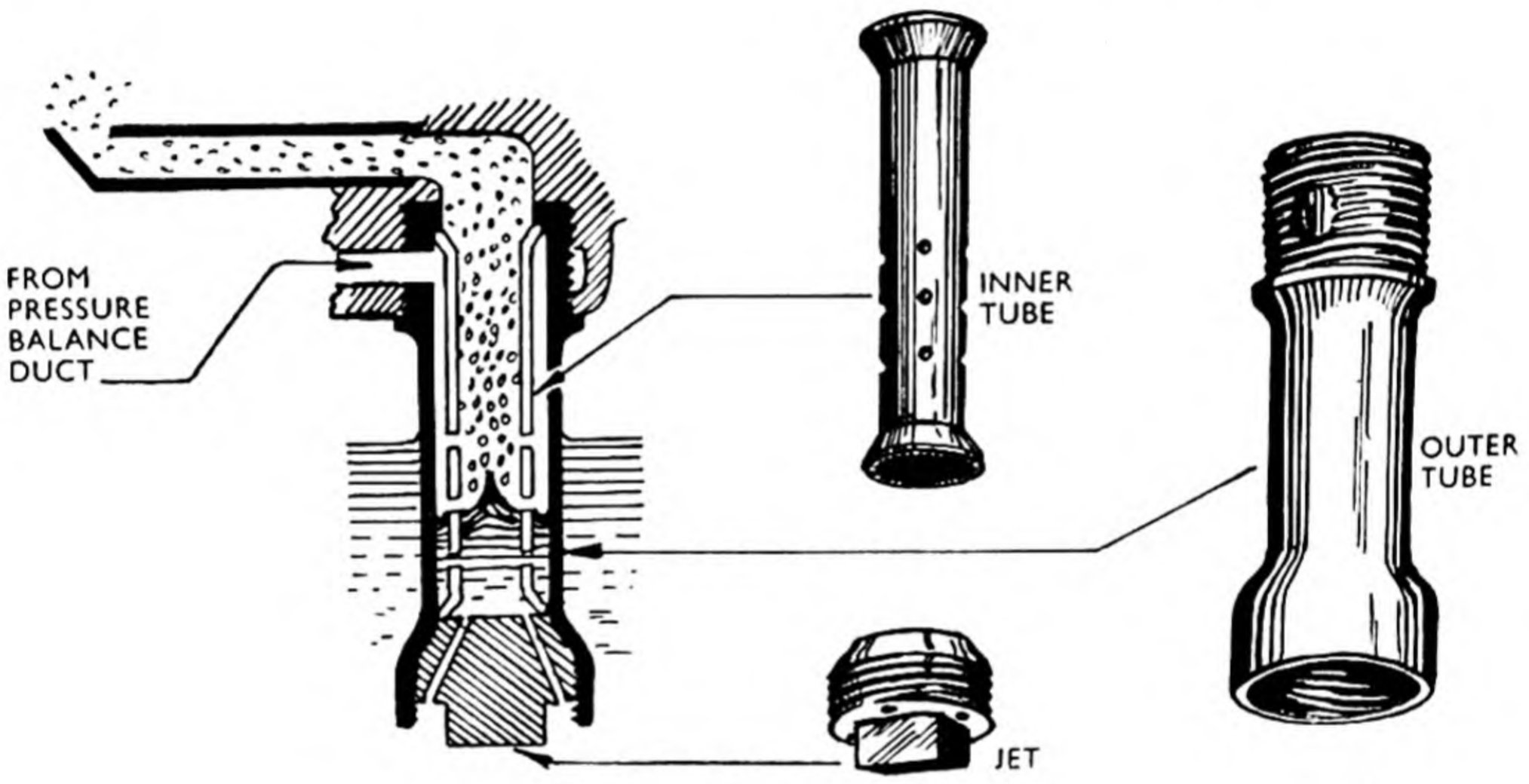


Fig. 20.—Hobson diffuser

flows through it into the duct. This air, flowing up round the main jet, partially relieves the depression at this point caused by the Venturi effect, and so the normal duct, too, begins to deliver fuel in less proportion than it would otherwise do. Suitable choice of jet sizes enables an almost constant mixture strength to be maintained.

The other device used to fulfil the same purpose is the diffuser. This not only keeps the proportion of petrol and air constant over the range of normal throttle openings, but serves an additional purpose in that it emulsifies the fuel by an early admixture of a small quantity of air, so that petrol reaching the choke tube is already broken up into small droplets.

The diffuser, as fitted to Hobson carburettors, is shown in fig. 20. It consists of two concentric brass tubes with an annular space between them. The inner tube leads directly to the petrol outlet in the choke, and is therefore subject to the lowered pressure at that point. The main jet, consisting of a brass plug drilled with four small holes,

allows petrol into the bottom of this tube. So far the device is merely a normal submerged jet.

The inner tube, however, is perforated by three rows of small holes. As the throttle is opened, and more fuel drawn from the outlet, the level in the tube falls and uncovers the holes one by one. The narrow annular space or well outside is also drained, and, since this outer space is connected to the pressure-balance duct, air flows in through the holes. The result of this " air bleed " into the main outlet is partly to relieve the depression there, so that fuel is drawn from it

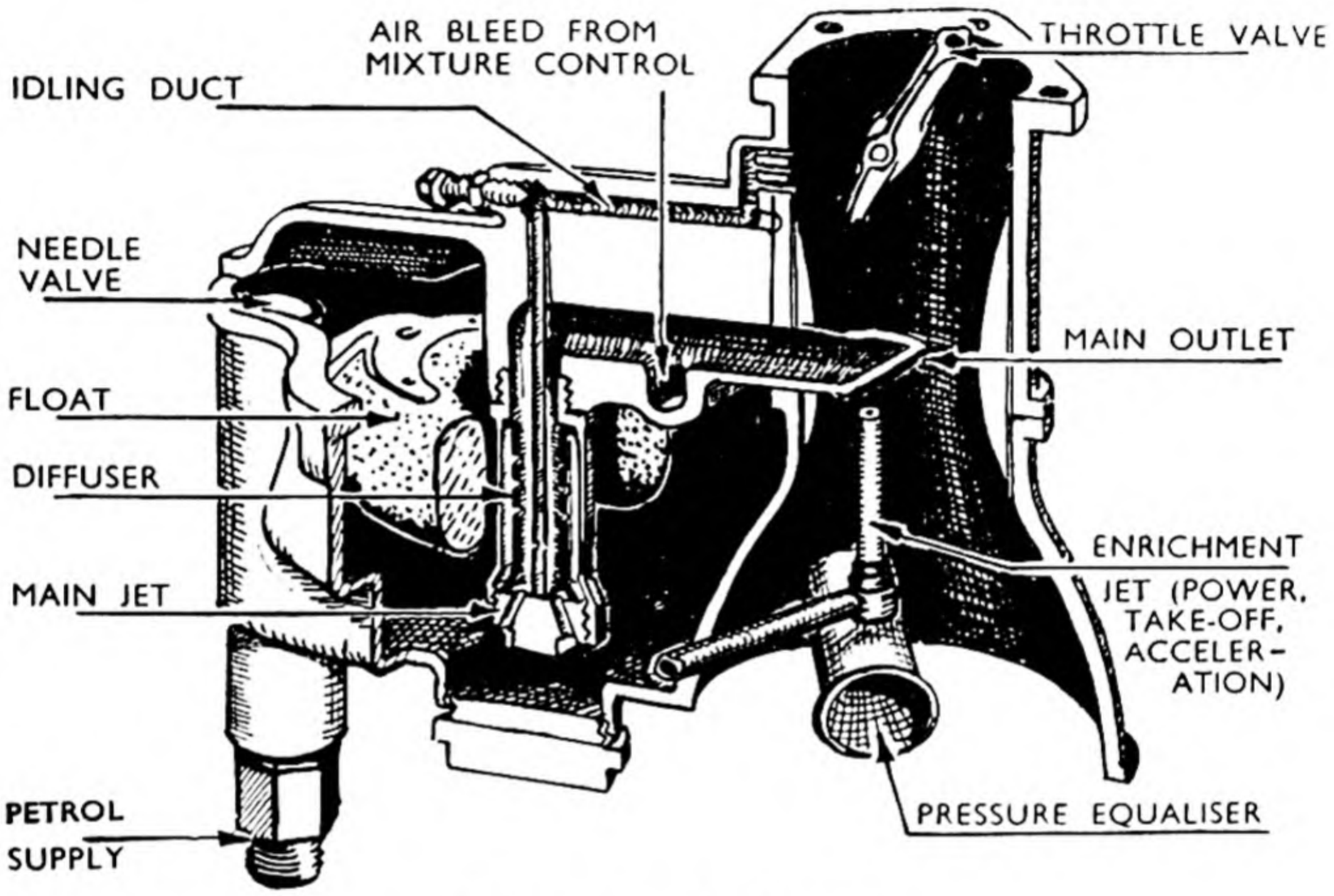


Fig. 21.—Aircraft carburettor

at a less increased rate than would normally be the case. The air bleed increases at still higher engine speeds as more of the holes are uncovered, and so, in the manner described, enrichment is prevented at all normal throttle settings, that is, throughout the cruising range, and only sufficient extra petrol is drawn from the jet to maintain a constant proportion of petrol to air. It must be emphasized that the diffuser does *not* maintain a constant proportion of petrol to air by adding air to the mixture passing through the choke. The very small quantity of air passing from the pressure-balance duct to the petrol outlet by way of the diffuser is merely diverted from the main airflow, and its purpose, anyway, is only to modify the rate of petrol flow by spoiling the Venturi pressure drop in the petrol duct.

Normally the diffuser supplies a mixture slightly richer than the chemically correct mixture, which would give theoretically exact

burning of all petrol and oxygen in the air. This is used when full power is required for long periods. For economical cruising at reduced power, a mixture control lever operated from the cockpit modifies the action of the diffuser so that a mixture slightly weaker than chemically correct is employed.

A section of a diffuser may be seen in the small aircraft carburettor illustrated in fig. 21.

Mixture Ratio at Throttle Openings other than Normal.

1. *IDLING.* When the throttle is almost closed, the speed of the air through the choke tube is not fast enough to produce a depression sufficient to draw petrol from the main outlet. However, the small quantity of air that is flowing must go through the narrow gap between the edge of the throttle valve and the side of the choke tube. The increase in speed through this very narrow gap gives a sufficient reduction in pressure to draw petrol through one or two small holes situated on the side of the tube, immediately opposite the gap. These holes communicate directly with the petrol in the centre of the diffuser well, as shown in fig. 22. This is called the " Idling or Slow-running Device ". It supplies a rich mixture and supplies it when the normal jet is inoperative. The rich mixture is specially useful when the engine is starting up from the cold, for under these circumstances some of the petrol does not evaporate, and is left on the side of the manifold walls. When starting a cold engine, even the slow-running device is sometimes insufficient to provide enough vaporized fuel for combustion. In this case *priming* is resorted to. This consists merely of squirting enough petrol into the induction system to provide a combustible mixture in the cylinders. Too much petrol will prevent starting, and the airman who overprimes will find that he must turn the propeller backwards two or three times in order to clear the cylinders of excess fuel.

2. *RATED POWER AND TAKE-OFF.* A richer mixture is needed if full power is to be developed when the engine is operating with throttle fully open for short periods. With the throttle in a position to give the normal maximum power from the engine (rated boost), a special jet comes into action and supplies enough petrol to give a mixture some 15 per cent richer in petrol than is chemically correct. This jet delivers its fuel either through a special nozzle protruding into the choke tube, or into the main outlet above the diffuser. This extra jet, called the *power jet*, is normally closed by a spring-loaded valve, but the valve is opened at a certain throttle

position (marked Rated Boost) by a cam attached to the layshaft of the throttle lever.

When the throttle lever is moved right to the end, for the extra power required in take-off, the mixture is still further enriched by another and similarly operated jet called the *enrichment jet*. With both extra jets open a mixture from 22 per cent to 50 per cent richer in fuel than the chemically correct mixture is supplied. With such a rich mixture some of the petrol is still in the form of small droplets when it reaches the cylinders. These droplets absorb heat on evaporation, and the cooling effect prevents detonation.

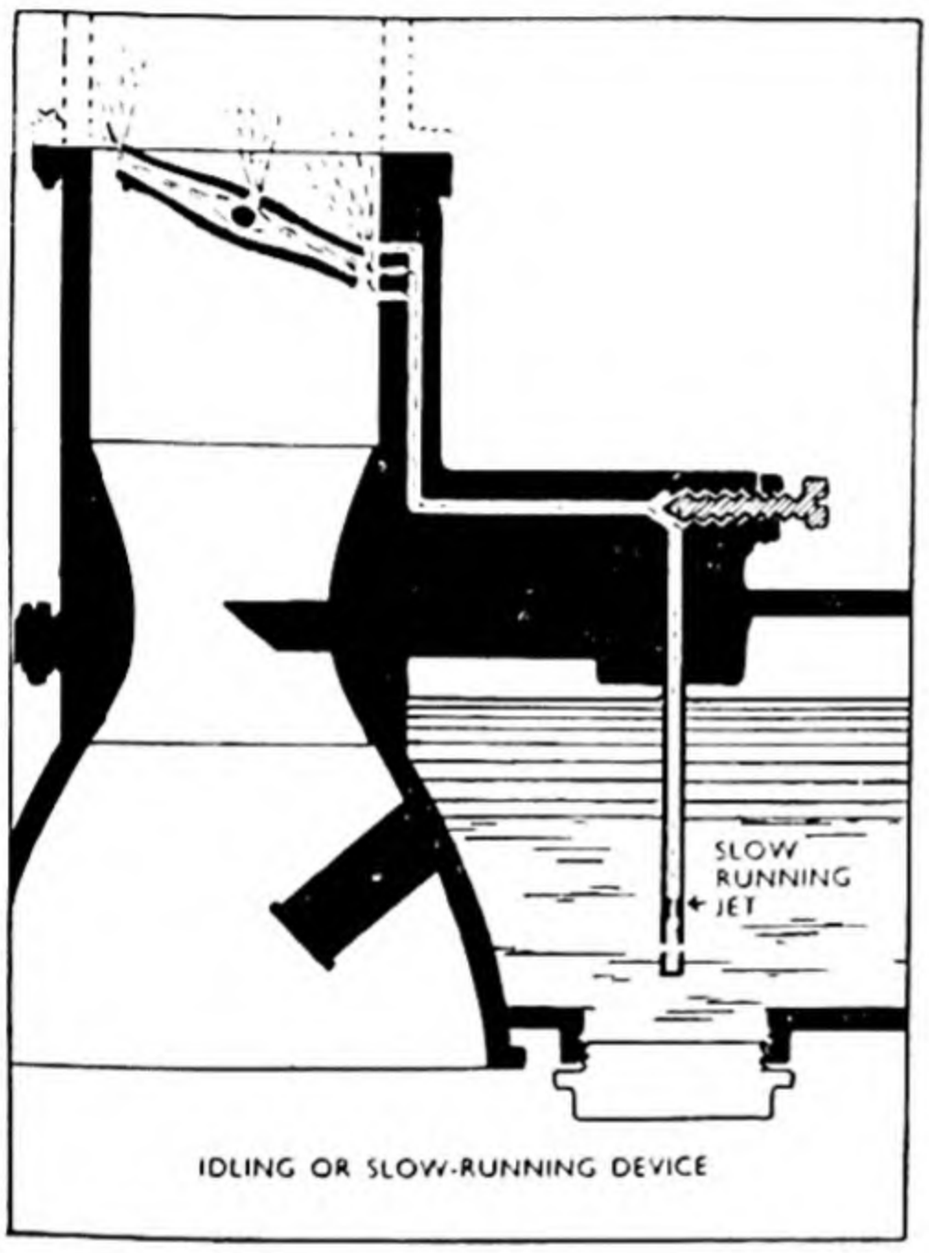


Fig 22.

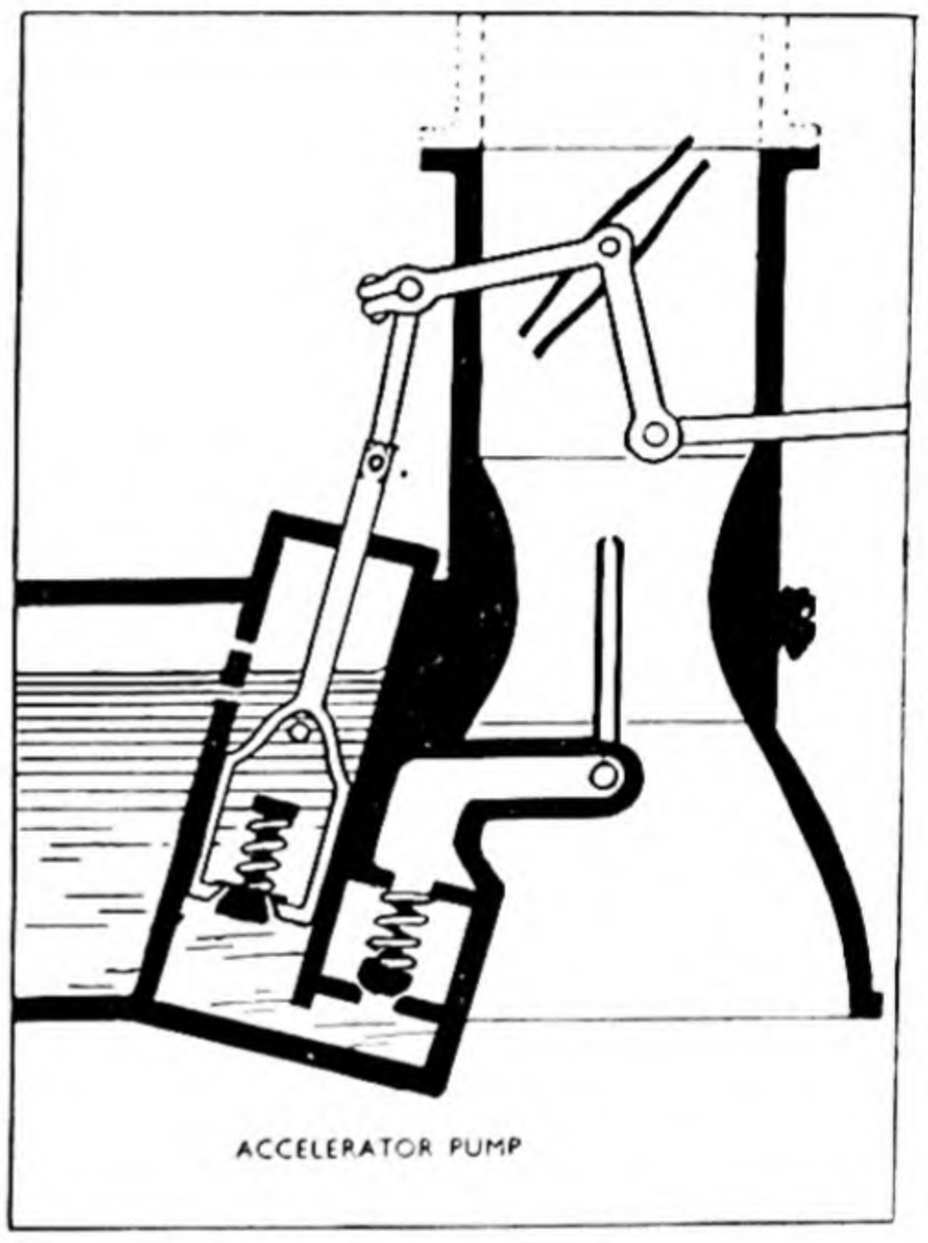


Fig. 23

The use of two separate jets is but one way of ensuring a sufficiently rich mixture at full rated power and take-off. A more direct method is employed in S.U. carburettors. This is illustrated on the right-hand side of fig. 26 (p. 140). As the throttle is opened pressure in the induction manifold rises. This rising manifold pressure is made to operate the enriching mechanism. A pile of aneroid capsules are mounted in a compartment built integrally with the carburettor unit. These capsules may best be described as small disc-like hollow boxes, made of metal thin enough to be flexible, and exhausted of air. A pile of capsules of this sort responds to a change of outside pressure by contracting or expanding somewhat after the manner of an accordion. The aneroid unit finds a number of applications in aircraft engines and instruments; in this case manifold pressure is

allowed to act upon it. When, on opening the throttle, the manifold pressure increases, the capsules contract. This movement is made to lift a tapered needle that partly blocks one of the orifices leading to the main petrol outlet. The gap between the needle and the rim of the orifice is enlarged, and the petrol flows more freely. An addition to the mechanism not shown in the diagram prevents the enrichment device from coming into operation before a certain throttle setting is reached.

Accelerator Pump.

As the throttle valve is opened for acceleration there is a tendency for the mixture temporarily to become lean. There are two possible reasons for this. In the first place, when the air speeds up, the petrol, which is heavier and more viscous than the air, does not leave the jets so easily. Secondly, the increase of pressure in the manifold that results from this extra flow causes some of the petrol vapour to condense on the sides. An accelerator pump is therefore fitted, which,

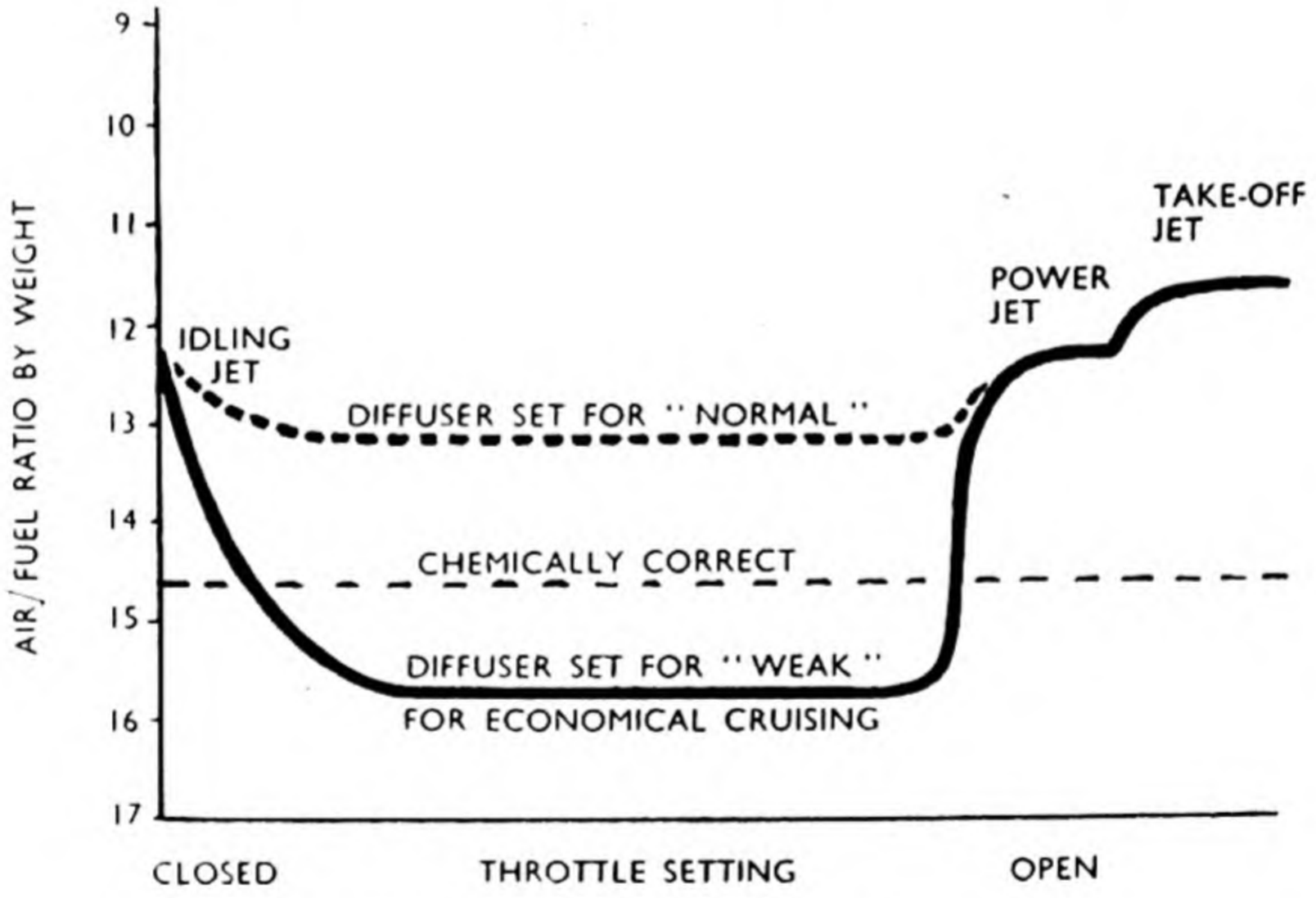


Fig. 24.—Throttle curve for Hobson carburettor

when the throttle lever is moved towards full power, injects a " shot " of petrol through one of the jets, for otherwise a momentary loss of power might be experienced on opening the throttle. Fig. 23 shows, in a simplified form, the accelerator pump fitted to the carburettor of fig. 21.

It may be well to recapitulate at this stage the points so far dealt with.

The simple carburettor will supply a mixture of correct propor-

tions for one throttle opening only; enrichment results if the throttle is opened wider and engine speed increased, whilst the proportion of petrol to air will decrease as the throttle is closed and engine speed drops.

Over the cruising range of throttle openings the engine must be supplied with a mixture of constant strength, either normal or, for economical cruising, some 10 per cent weak in petrol. A compensating jet or diffuser modifies the simple carburettor to provide a constant mixture of the right strength.

At either end of the range of throttle openings the carburettor must supply a mixture richer than is chemically correct for various reasons. In the closed position, when the engine is idling, or turning over slowly, the slow-running jet gives a rich mixture. This mixture drops to cruising strength as the throttle is opened. At the other end, the mixture is enriched for full power; and further enriched to prevent detonation for take-off. This is done either by special power and enrichment jets, or by enlarging one of two twin main jets by a needle valve.

For those who like graphs and tables the whole story of mixture control for various throttle settings is told by the following table and accompanying graph (fig. 24):

Requirement	Means
1. Constant mixture at all normal throttle openings.	By diffuser or compensating jet.
2. Rich mixture for idling.	By slow-running device.
3. Rich mixture at full rated power in order to develop full power.	By additional power jet or needle-valve jet.
4. Extra rich mixture to avoid detonation at take-off throttle setting.	By enrichment jet or further movement of needle in needle-valve jet.
5. Extra fuel for acceleration.	Accelerator pump.

EFFECT OF ALTITUDE ON CARBURATION

A carburettor fitted with the devices described would operate very successfully so long as the aircraft continued to fly at one level (for which the carburettor would have to be suited), but would suffer from a grave fault: the mixture it would deliver at any throttle setting would *become richer as the aircraft rose to greater heights*.

To explain fully how this happens would demand a mathematical development of Bernoulli's theorem as it applies to the Venturi tube of the carburettor, and this is beyond the scope of this book. The facts must be baldly stated, and are as follows.

At increased altitudes the density of the air is less than at ground level. At a constant engine speed the volume of air drawn into the cylinders will be the same at both levels in an unsupercharged engine, but because of its decreased density, the weight of air entering the cylinders is smaller at the higher altitude.

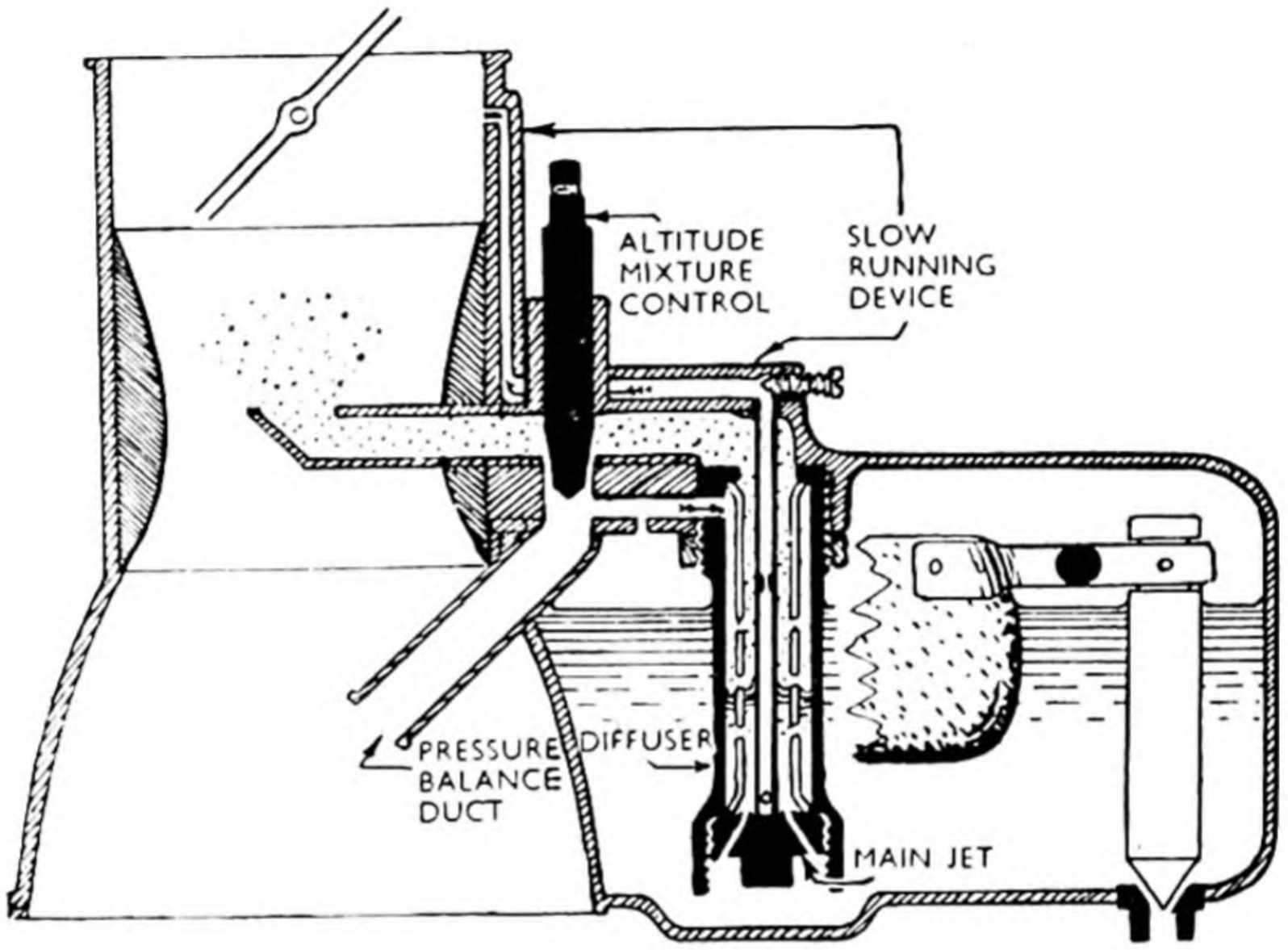


Fig. 25.—Aircraft carburettor

The petrol drawn from the outlet is also less, since the actual depression at the choke is proportional to air density (which has decreased), but *the fall in petrol flow is not so rapid as the fall in the weight of air*, and so *the mixture becomes richer as the aircraft rises.*

Some method must be used to counteract this tendency, by diminishing the fuel supply at altitude. This may be achieved either by decreasing the suction at the choke, or by decreasing the size of the jet that meters the fuel. Both methods are in use, the former in Hobson instruments, and the latter in the S.U. carburettors.

Fig. 25 shows the principle of the Hobson method. Air from the pressure-balance duct is allowed to leak into the top of the low-pressure centre tube of the diffuser. In some smaller carburettors the leak is controlled by the withdrawal of a slightly tapered plunger from a hole leading from normal to low pressure. In larger carburettors the valve that permits the air leak is of a conical form and rotates

in a way similar to an ordinary tap. The former type is illustrated here.

In small engines such as the Gypsy Major installed in the Tiger Moth aircraft, the mixture control at the side of the throttle lever in the pilot's cockpit is linked directly with this plunger or tap. Up to 5000 ft. above mean sea-level the mixture lever is kept at "fully

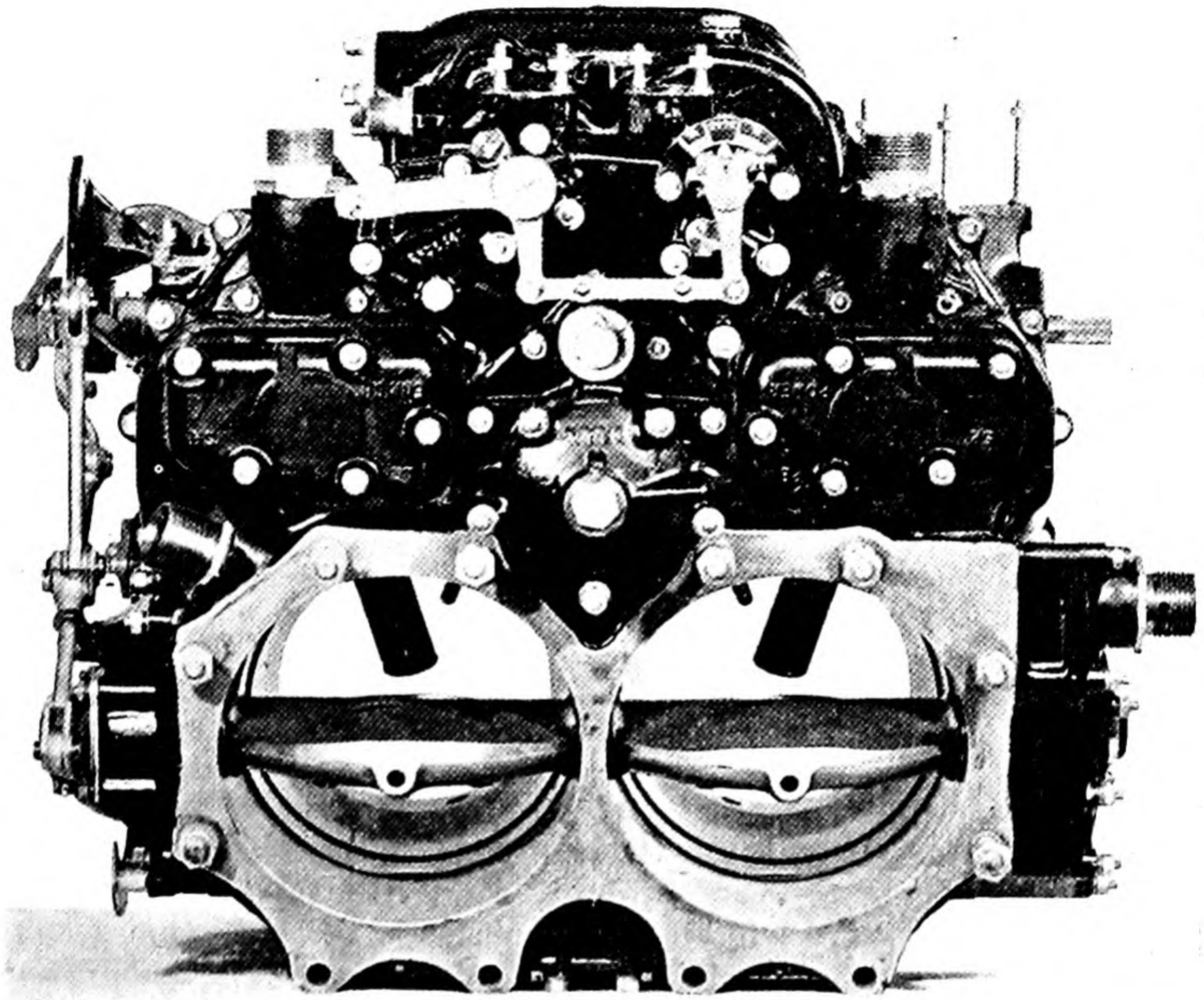


Fig. 25*a*.—The Claudel-Hobson A.I.T. 132-M.C. carburettor fitted to the Bristol Hercules engine, showing twin intake and throttle valves

(*By courtesy of Hobson Components, Ltd.*)

rich"; above this altitude the lever is moved towards "lean". This is often carelessly referred to as weakening the mixture at altitude; what it actually does is to prevent its becoming richer.

Hand control of mixture in this way is open to misuse, for it is difficult for an inexperienced pilot to know just what proportion of petrol he is allowing to mix with the air. In an effort to avoid overheating the engine by the use of mixtures nearly correct, he will usually employ too rich a mixture, thus curtailing the range and ceiling of the

aircraft. The introduction of an automatic altitude mixture control was therefore a notable innovation, for it renders any such misuse impossible. The principle of automatic control is simple. The essential component is a bank of aneroid capsules, the outside of which is subject to atmospheric pressure. As the pressure of the air decreases with increase in altitude the capsules expand, and this movement is made to operate the mixture control.

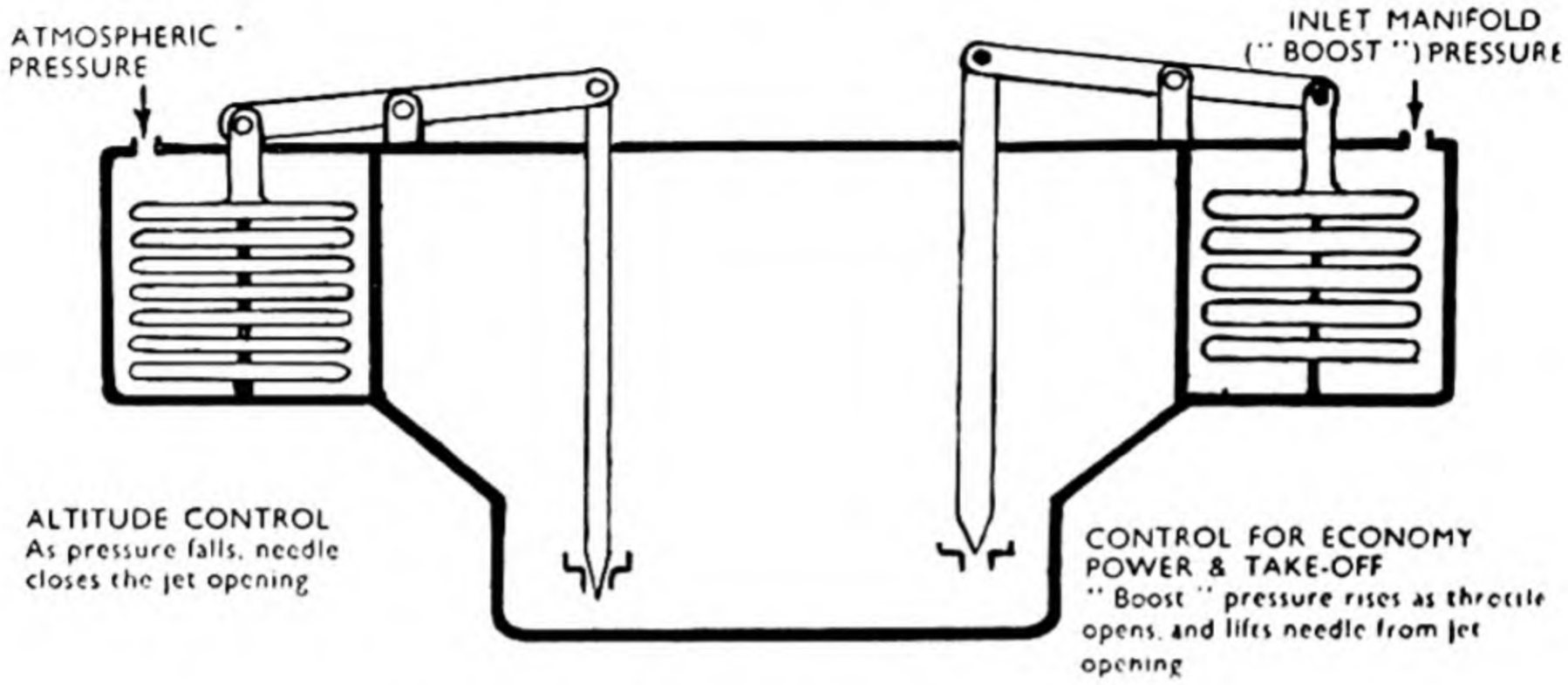

ATMOSPHERIC PRESSURE
INLET MANIFOLD (" BOOST ") PRESSURE
ALTITUDE CONTROL
As pressure falls, needle closes the jet opening
CONTROL FOR ECONOMY POWER & TAKE-OFF
" Boost " pressure rises as throttle opens, and lifts needle from jet opening

Fig. 26.—Principle of S.U. carburettor control

The needle valve of the S.U. carburettor is lifted directly (see fig. 26), but the air-bleed tap on the Hobson carburettors requires a larger force, and is turned through the action of a relay that uses the pressure of the oil in the lubrication system of the aircraft.

Icing.

One great danger with the carburettor is the possibility of ice formation in the choke tube and around the throttle valve. If this happens the throttle valve will stick and, perhaps, the induction system be so blocked as to upset the mixture proportion, and even prevent any mixture reaching the engine at all. The somewhat dangerous method of blowing away the ice by a deliberate backfire of the engine is not to be recommended, for it may remove the throttle valve as well!

It must be carefully noted that ice may form when the outside temperature is well above freezing-point, for there is a considerable drop in temperature at the choke. There are two reasons for this: one is the cooling that takes place as a result of expansion at the low pressure induced by the Venturi constriction; the other is the cooling that results from evaporation of the petrol. Between them these two factors may produce a temperature drop of as much as 25° C.

Flying through supercooled water droplets will cause severe icing of the carburettor, adding to the danger of ice formation on the aircraft itself.

Attempts have been made to reduce the danger of ice formation in the choke tube by taking the warm lubrication oil, or sometimes the warm coolant, through a jacket around the carburettor. In one engine, the coolant surrounds the carburettor and lubrication oil circulates through the hollow throttle valve. In other engines, the pilot, by means of a lever, can divert some of the hot exhaust gases and pass them around the carburettor to remove any ice that has formed inside. When the pilot is able to control the degree of carburettor warming, the possibility of overheating the exhaust gases must be guarded against, for if this happens mixture proportion may be upset, and, in addition, loss of engine power will result from the low density of the hot air.

Injection Carburettors.

It has been thought advisable to describe in some detail the principle underlying the types of carburettor which the reader is most likely to meet, but though some of these principles of metering the fuel are common to many carburettors, there are other ways of approaching the problem of carburation.

In many American aircraft fuel is injected under positive pump pressure instead of by means of the Venturi principle. The Bendix-Stromberg injection carburettor employs this method. The fuel is sprayed into the induction system at a point beyond the throttle valve. There is no float chamber. A small Venturi tube is situated in the mouth of the carburettor, but its purpose is only to regulate the supply of fuel.

Two main advantages are claimed for this type of carburettor:

1. No ice formation due to vaporization of the fuel.
2. Complete manœuvrability. One of the faults associated with the float-chamber type of carburettor is its tendency to cause " cutting out " if the aircraft is flown upside down.

Direct injection is a standard feature of German and one or two American aircraft. In this case the fuel is sprayed under pressure directly into the cylinder through a nozzle situated near the valves. The same advantages are claimed for direct fuel injection as for injection carburettors, namely, freedom from icing and complete manœvrability. In addition, somewhat lower grades of fuel may be employed without detonation, at compression ratios equal to those that

demand high-octane petrol when fed through a carburettor. This may be due to the cooling of the cylinder head and the exhaust valve in particular, caused by the evaporating fuel.

This method has, however, certain disadvantages, and is on the whole more bulky, more complicated, and less reliable than the method employed in this country.

The Complete Fuel Supply System.

Although this chapter has dealt almost entirely with carburettors, the complete fuel system includes in addition the fuel tanks, filters, pipes and cocks for leading the petrol from any tank the pilot selects to the carburettor, fuel gauges, and, if the fuel is pressure fed to the float chamber, the fuel pump and fuel pressure gauge.

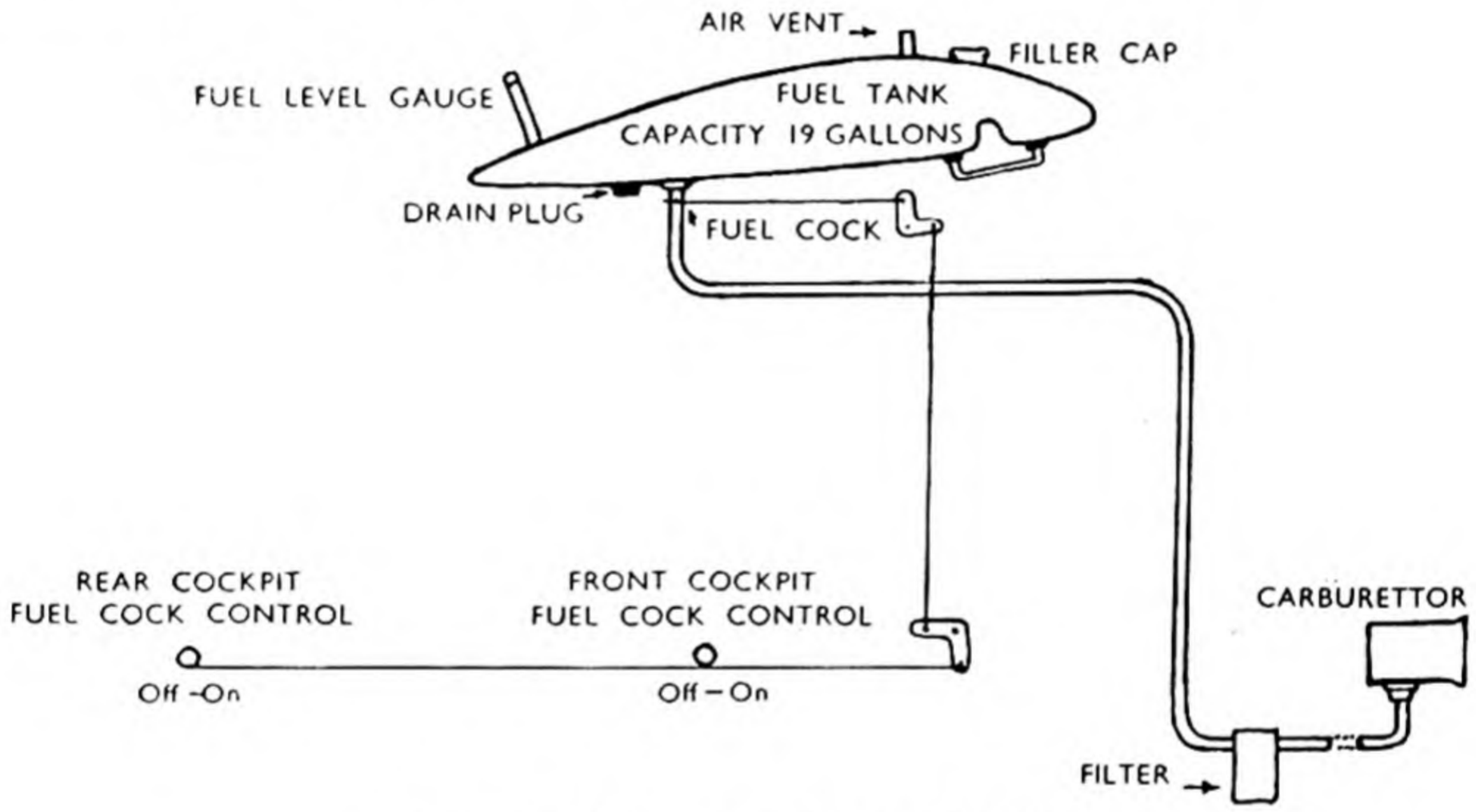


Fig. 27.—Fuel system of a Tiger Moth

In small aircraft the fuel is often allowed to fall by its own weight to the float chamber, and a typical gravity-fed fuel system of this type, as found in the Tiger Moth aircraft, is shown schematically in fig. 27. The single tank forms part of the centre section of the upper wing.

When the tanks are situated below the level of the carburettor the float chamber must be supplied from the fuel tanks by means of an engine-driven fuel pump. Larger aircraft almost invariably use this method when gravity feed from tanks far out in the wings would be too unreliable. Hand pumps are usually fitted in addition in case the mechanically operated pumps fail.

QUESTIONS

1. Draw a diagram of the simple carburettor, labelling the parts.

2. (*a*) What are the two primary functions of the carburettor?

(*b*) In what way does the simple carburettor fail to fulfil its proper functions with increase in altitude?

(*c*) What is the purpose of the accelerator pump?

3. (*a*) Explain the action of the choke tube in drawing fuel from the float chamber in the simple carburettor.

(*b*) Give two defects of the simple carburettor that make it unsuitable, as it stands, for the aircraft engine.

4. (*a*) What is the purpose of the diffuser in the aero-engine carburettor?

(*b*) Why may icing-up of the carburettor occur when the temperature is higher than freezing-point?

(*c*) How may the pilot prevent this icing in some engines?

5. (*a*) What, briefly, are the functions fulfilled by the following parts of the aero-engine carburettor:

1. The jet?
2. The choke tube?
3. The float and needle valve?

(*b*) Explain briefly why the mixture should be rich for:

1. Starting-up from cold.
2. Take-off.

6. (*a*) What is the effect on the mixture ratio delivered by the simple carburettor of an increase of throttle opening?

(*b*) What part of the aero-engine carburettor is used to overcome this defect?

(*c*) Explain the action of the idling jet.

CHAPTER XII

How the Engine Breathes: the Supercharger

VOLUMETRIC EFFICIENCY. EFFECT OF ALTITUDE. SUPERCHARGER CONSTRUCTION. PROBLEMS OF SUPERCHARGING. TWO-SPEED SUPERCHARGERS. TURBO-DRIVEN SUPERCHARGERS. AUTOMATIC BOOST CONTROL.

A petrol engine derives its power from the burning of petrol and air. The motor-car owner is apt to regard the former of these two partners in the process of combustion as the more important. This is natural, as he has to pay for it and has more trouble in obtaining it. But from the point of view of the engine designer the air is even more important than the petrol, for it is harder to get the right amount of air into the cylinders than the right amount of petrol. Petrol is compact and easy to handle, whereas air is just the opposite.

In order to burn 1 lb. of petrol, from 12 to 15 lb. of air are needed. For every gallon of petrol used, about 1200 c. ft. of air must be made to enter the engine. The internal-combustion engine must therefore be designed to handle very large quantities of air. In fact the engine is really an air pump, and the power that can be obtained from it depends on how much air it can draw in. The small amount of petrol can always be supplied. The conception of the engine as primarily a machine for handling air is fundamental to a good understanding of the principles of the internal-combustion engine.

This explains why an increase in the bore or stroke of the cylinders, or in their rotational speed, usually results in an increase of power.

Volumetric Efficiency.

It might be expected that the cylinder would draw in on each induction stroke a volume of air equal to the swept volume, and this is approximately true. The really important thing, however, is not the volume, but the *weight* of air that enters on each induction stroke.

Now because of the resistance offered by the intake manifold, and even more, by the intake port, there is a distinct pressure drop of the air on its way to the cylinder even when the throttle valve is wide open. This means that the pressure, and therefore the density of the air

on the cylinder side of the intake port, during the induction stroke is always less than that of the atmosphere surrounding the aeroplane. In this state, each cubic foot of air in the cylinder weighs less than a cubic foot of air outside.

Another factor tending to reduce the weight of air (or mixture) drawn into the cylinder is the temperature of the charge at the time the inlet valve closes. The inlet manifold maintains a temperature about equal to the boiling-point of the petrol, and the cylinder and piston are even hotter. As it passes from the carburettor to the engine the air is warmed, and warmed air will always weigh less per cubic foot than cold air at the same pressure.

If it were possible to leave the intake valve open long enough for the pressure inside and outside to become equal, and if, in addition, the parts of the engine were no warmer than the ordinary air outside, then, under these circumstances, a greater weight of air would fill the cylinder than actually does so. The engine would be a more efficient air pump, and other factors being equal, it would deliver more power when the oxygen in the air was burnt. Unfortunately, this ideal state of affairs can only be obtained by "turning over" the engine infinitely slowly whilst it is cold, but although such an operation is of no practical use, it may be used as an imaginary standard, against which the actual usefulness of the engine as an air pump may be assessed.

This is the idea that lies behind the definition of *volumetric efficiency*. This quantity is defined as follows:

$$\frac{\text{Weight of mixture entering cylinder per stroke}}{\text{Weight of mixture to fill swept volume at normal temperature and pressure}} \times 100 \text{ per cent.}$$

Normal temperature and pressure are precisely defined in order to give an exact value to the standard part of this expression.

They are taken as 15° C. and 14·7 lb./sq. in.

The design of the engine has an important bearing on volumetric efficiency; the passage of the air through the "air scoop" and carburettor, along the inlet manifold, through the inlet valves should be as unrestricted as possible. It is for this reason that the Merlin engines have twin inlet ports and valves in each cylinder.

The timing of the valves has a considerable effect, and it has been explained how the momentum of the inrushing charge is utilized by leaving the inlet valve open until some way past B.D.C. in order that the largest possible weight of air (and therefore mixture) may be drawn in.

Finally, the temperature of the charge should be as low and the pressure outside the inlet valve as high as possible, consistent with other practical considerations. It is these last two factors that are to be dealt with in this chapter.

Effect of Altitude.

We live at the bottom of a sea of air, the lower layers of which are pressed down by those above. Atmospheric pressure is a measure of the weight of the overlying air, and an observer who set out with a barometer to measure this pressure at different levels would discover that his barometer readings diminished in a regular manner as his height above the earth's surface increased. If the air were to have the physical properties of sea-water, this would be the end of the matter, but all gases are easily compressible, and the lower layers of air, subject to a greater pressure than layers above, are compressed into a smaller volume. A cubic foot of air at ground level contains more air by weight than a cubic foot at any point above it: in scientific terms, *its density decreases with increase in altitude.* The same thing would be noted of a pile of porous rubber blocks, and anyone buying by the cubic foot from such a pile would choose from the lower layers if he wished to get the most for his money.

It is also well known that the farther the air is from the warmth of the earth's surface, the colder it becomes, and on this account it might be expected, according to well-established laws governing the behaviour of all gases, that the density of the air would increase as it became colder. The two factors, temperature and pressure, have opposite effects, but the density of the atmosphere decreases with increase in height, for the effect of pressure is predominant: the part the temperature plays is a very small one (fig. 28).

An engine operating at any considerable height above the earth's surface is surrounded by " thin " air, and although it may pump in as many cubic feet as at ground level, it finds difficulty in getting a sufficient *weight* of it (fig. 29).

It is interesting to note, by way of analogy, that what is true of a petrol engine is also true of a human being. The human being is also an internal-combustion engine, which gets its " fuel " from food. The food is " burnt " or oxidized by the air taken into the lungs. On the top of a high mountain the human engine finds difficulty in taking in a sufficient weight of air, and partly adapts itself by deeper and more rapid breathing. The human engine that attempts even greater heights by flying in an aircraft must have its oxygen supply augmented from a separate source.

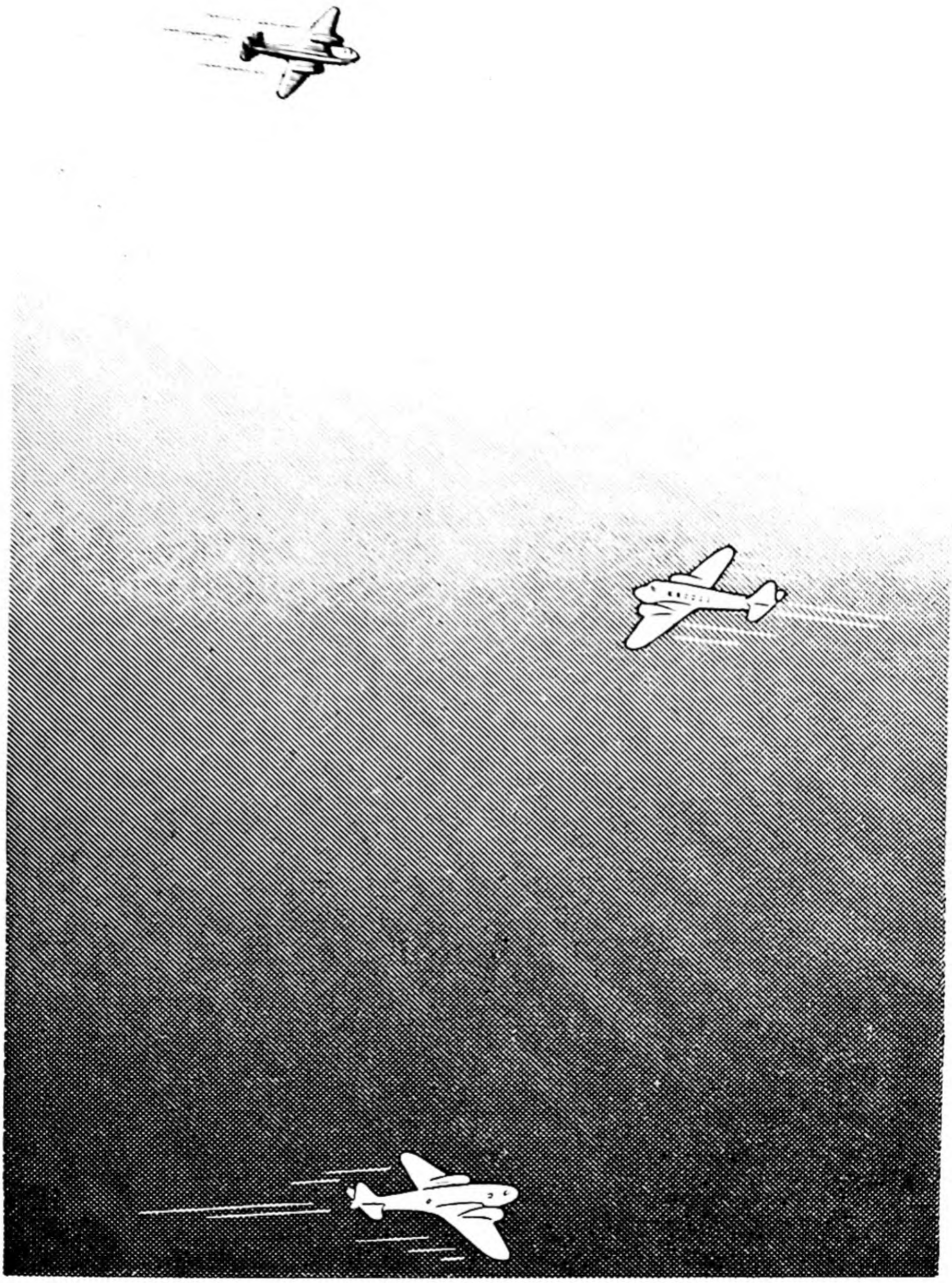


Fig. 28

(*By courtesy of General Motors, Detroit, Mich., U.S.A.*)

The aircraft engine also finds a difficulty in breathing. It has been shown how power depends on the amount of air by weight that passes

into the cylinders: the term " Volumetric Efficiency " has been used to express this idea numerically. It is clear that there will be a progressive falling off in volumetric efficiency as the aircraft climbs.

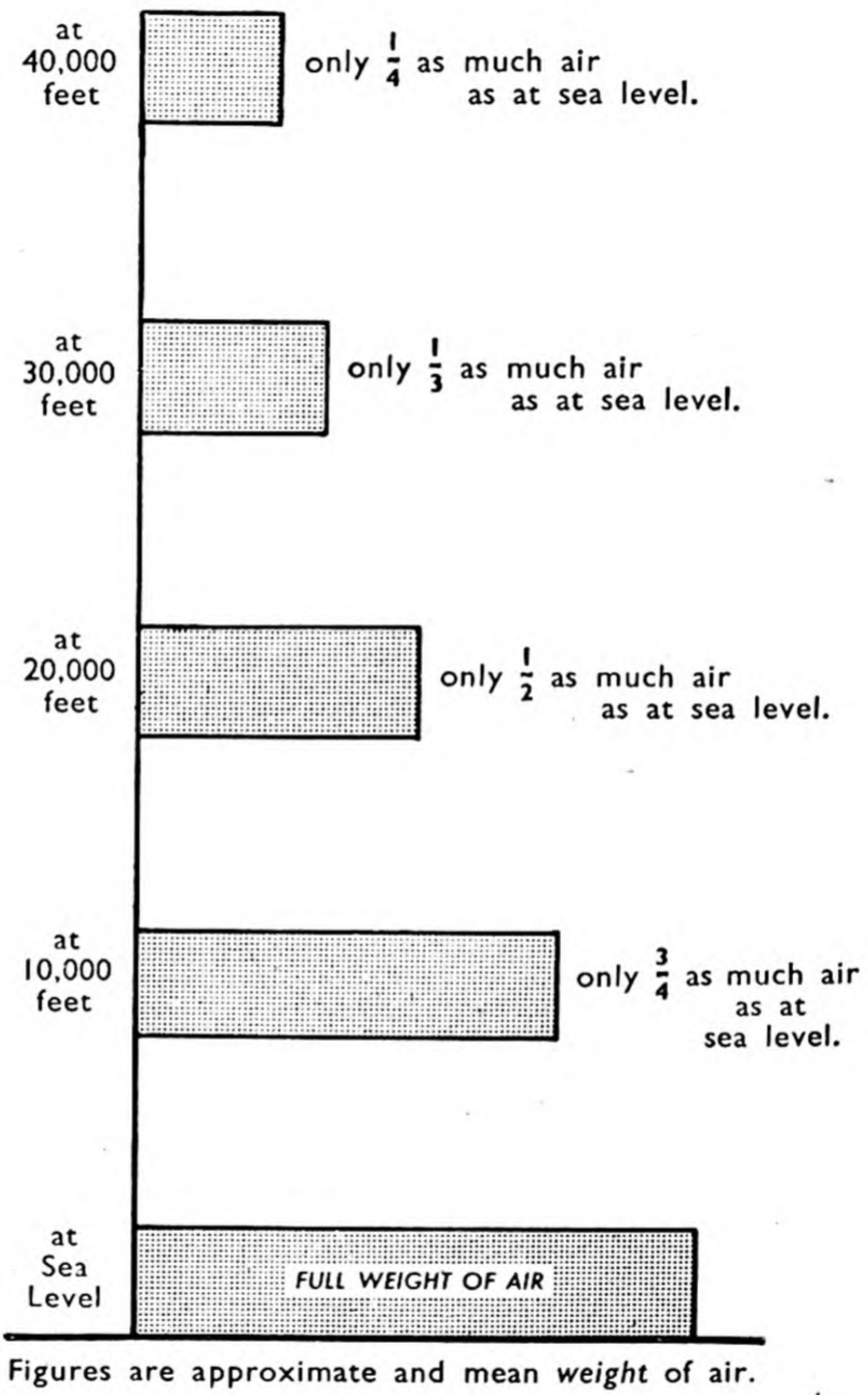

UNLESS SOMETHING IS DONE TO OFFSET DECREASING DENSITY, ENGINE WOULD GET—
at 40,000 feet
only 1/4 as much air as at sea level.
at 30,000 feet
only 1/3 as much air as at sea level.
at 20,000 feet
only 1/2 as much air as at sea level.
at 10,000 feet
only 3/4 as much air as at sea level.
at Sea Level
FULL WEIGHT OF AIR
Figures are approximate and mean weight of air.

Fig. 29

(By courtesy of General Motors, Detroit, Mich., U.S.A.)

The serious effects of decreased air density may be overcome if some means can be found of deceiving the engine into believing that it is still operating at ground level. This may be accomplished by supercharging.

The early supercharger was a pump or blower, the purpose of which was to maintain the pressure of the air in the intake manifold equal to its value at ground level. In this way, volumetric efficiency and the power output could be maintained up to an altitude called the *rated altitude*. Beyond this, the supercharger could not maintain the normal pressure in the manifold, and engine power began to fall off. In wartime, when victory usually goes to the aeroplane that can fly highest, this is of the utmost importance.

Supercharger Construction.

The supercharger consists of a simple centrifugal blower, engine-driven at high speed. The rotating member is called the *impellor*, and has the appearance of a flat disc or plate, bearing on one face a number of radial vanes. The speed of rotation of the impellor may reach 30,000 revolutions per minute, and the centrifugal forces that result cause considerable mechanical strain. The forces acting on the impellor tip at high speeds may be almost 100,000 times its weight. A small piece of the tip weighing 0·01 oz. may thus experience a force of 50 lb. acting radially from the centre. It is therefore important that only the highest grade of forging be used in its construction, and special care be taken to balance it properly. Air is drawn in at the centre of the impellor, is caught by the rotating vanes and flung outwards from the tips at great speed in the form of a vortex or whirlpool.

The air now encounters a fixed ring of deflector blades called the *diffuser*. This is a set of blades curved to leave the rim of the impellor tangentially, so that the air passes into the spaces between them without shock. The gap between each pair of blades in the diffuser widens from inside to outside, and in passing through these gaps the air slows down, with consequent increase in pressure—yet another example of the use to which the Venturi principle is put in the aircraft. Kinetic energy is thus exchanged for pressure energy.

The high-pressure air leaves the rim of the diffuser and passes into a tube or discharge casing, from which it travels to the engine.

Any turbulence within the supercharger only changes to heat energy, and contributes nothing to the building up of pressure. The blades of both impellor and diffuser, together with the inlet and outlet for the air, are all designed with the object of reducing turbulence to the minimum. Slight differences in detail are to be found when comparing the superchargers of various manufacturers. The impellor blades of the Merlin supercharger are bent round at the centre to give a lip, so that the air may enter smoothly. They are of the open type; that is to say, they are backed by a disc on one side only. This

calls for a very small clearance between the impellor and its casing if leakage of air is to be avoided. The impellor of the supercharger fitted to Bristol engines is of the box type, and therefore such small clearances are unnecessary. The Bristol supercharger is shown in fig. 30.

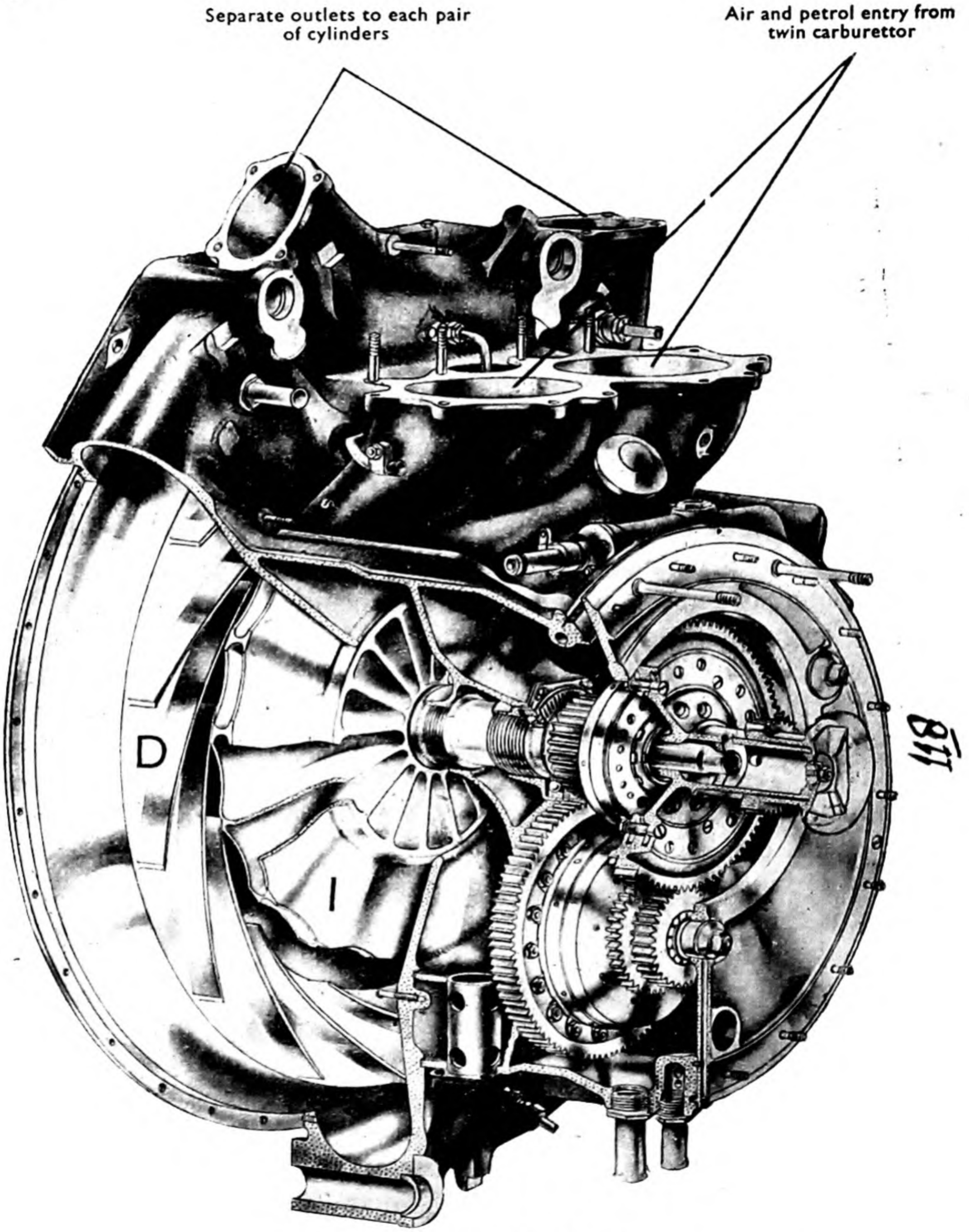


Fig. 30.—Gear-driven supercharger
I. Impellor. D. Diffuser
(*By courtesy of the Bristol Aeroplane Co.*)

The power to drive the supercharger is derived from the engine. On British engines the drive is taken directly through a train of gears, but an alternative is provided by the use of a turbine, driven by the exhaust gases from the engine. Some American superchargers employ this means of turning the impellor. The construction of a suitable turbine was fraught with difficulty, for the blades are called upon to endure the very high temperatures of the exhaust gases. Considerable research has led to the discovery of metals capable of standing this rough treatment, and the blades of the turbines used on such famous aircraft as the American Lightning, Fortress, and Thunderbolt operate successfully at dull-red heat. This turbo-supercharger offers some advantages over the gear-driven type, and these advantages will be dealt with later.

Problems of Supercharging.

The extra power that the supercharger enables the engine to deliver does not all reach the propeller shaft. A price must be paid, for some power is needed to drive the supercharger itself.

For example, the power of an unsupercharged, or normally aspirated engine, as it is called, will have fallen to about half its ground-level value at 20,000 ft. Suppose that it is required to restore the full power of a 1000-h.p. engine at this height. A net gain of 500 h.p. will be needed. A pumping apparatus of sufficient capacity will require about 100 h.p. to drive it, for it is generally reckoned that the supercharger absorbs about 10 per cent of the rated power of the engine.

Now, for reasons of safety, the full delivery of such a supercharger cannot be used near the ground. At 20,000 ft. it is doubling the pressure of the atmosphere surrounding it, in order to reproduce ground-level pressure in the manifold. If it were allowed to go on doing this when the aircraft was actually surrounded by air at ground-level pressure, the pressure inside would be far in excess of that for which the engine was designed. Detonation would certainly result, adding to already excessive pressure and temperatures in the cylinders: the engine would be severely damaged. Some means must be found for maintaining a constant air pressure in the manifold as the aircraft descends, and this means for controlling boost pressure is to be found ready to hand in the throttle lever and its throttle valve. By gradually closing the throttle, maximum permissible boost may be kept from fully open throttle to ground level.

Near the ground, therefore, the manifold pressure is no higher than in the same engine without a supercharger, and power is being

consumed by the supercharger to no good purpose. Under these conditions the normally aspirated engine would deliver more power. In the case of the example quoted the difference would be 100 h.p.

The accompanying graph (fig. 31) illustrates the difference between two similar engines, one without a supercharger, the other with a supercharger designed to maintain ground-level pressure up to 20,000 ft. The unsupercharged engine gives a better performance at ground level, but its power begins to fall off immediately as the aircraft climbs. The supercharged engine shows a slight increase in power as the aircraft climbs to rated altitude; at that height it actually

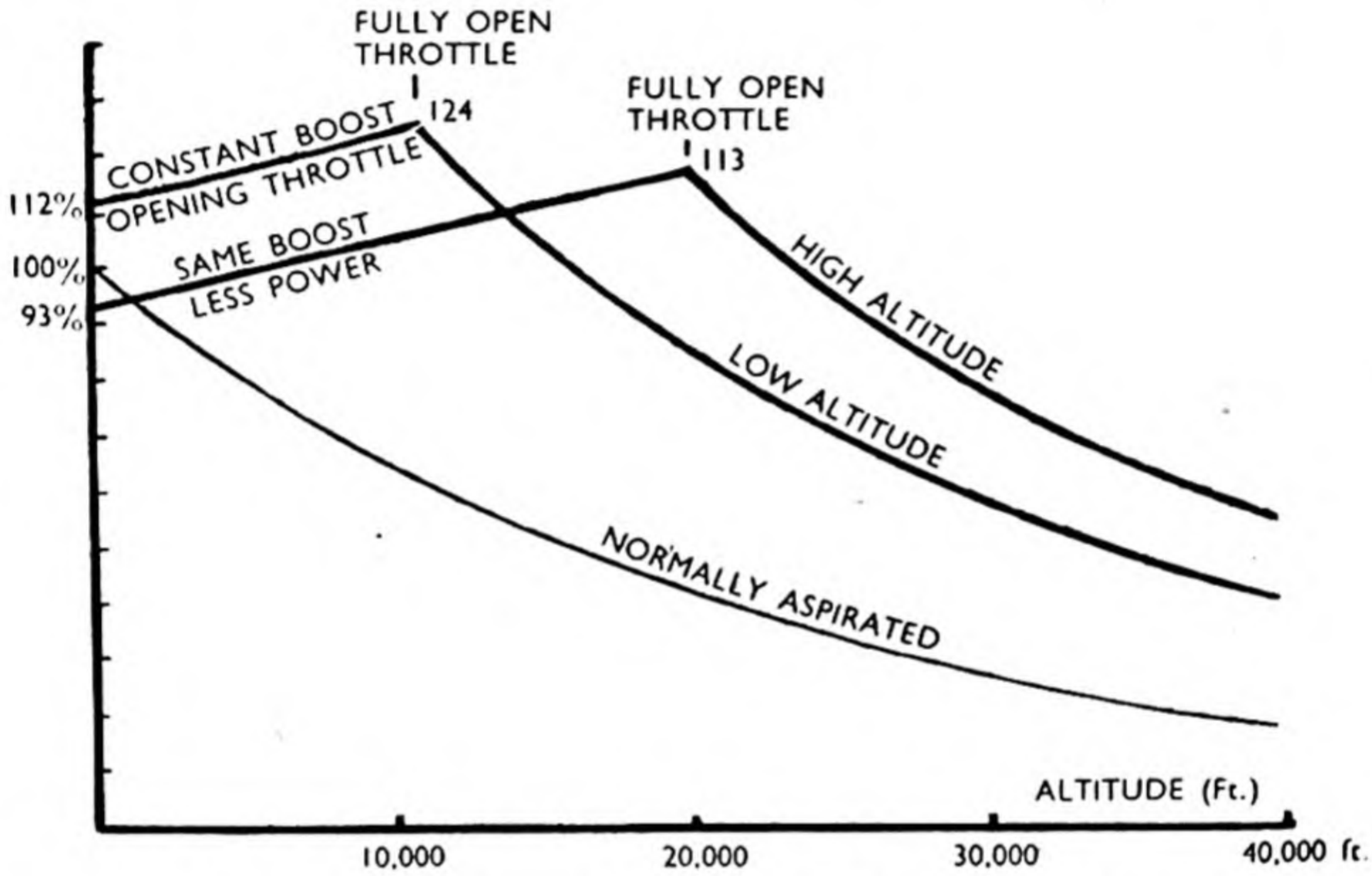


Fig. 31.—Comparison of high- and low-altitude superchargers

delivers more power than at ground level. Two factors contribute to this. One is the decrease of temperature that takes place with increased altitude; at *the same pressure* (and these are the conditions operating inside the manifold) the colder air will be denser, and some gain in volumetric efficiency is to be expected on this account. The other factor concerned is the decreased back pressure at the exhaust. This gives more efficient scavenging and a lower induction (or "suction") pressure. The throttle is gradually opened as the aircraft climbs until a height is reached at which the throttle is fully open. This is the height referred to as *rated altitude*. Beyond this point there is nothing "in hand", and the engine power shows a progressive decline similar to that of the unsupercharged engine.

The pilot should regard his throttle lever as a boost control, indirectly controlling engine power. The lever should not be advanced to give manifold pressure in excess of that for which the engine was

designed, and, when high boost is necessary for extra power, it should not be maintained for longer than is specified by the makers. A gauge indicates the actual pressure at any time inside the intake manifold. The British practice is to call this a boost gauge and have it reading in pounds per square inch above or below atmospheric pressure. In America the indicator is called a manifold pressure gauge and is calibrated in inches of mercury absolute. If atmospheric pressure is taken as 30 in. of mercury or 15 lb. per square inch, then a boost of plus 2 on one indicator would read as 34 in. on the other. The two different methods of calibration are illustrated in fig. 32.

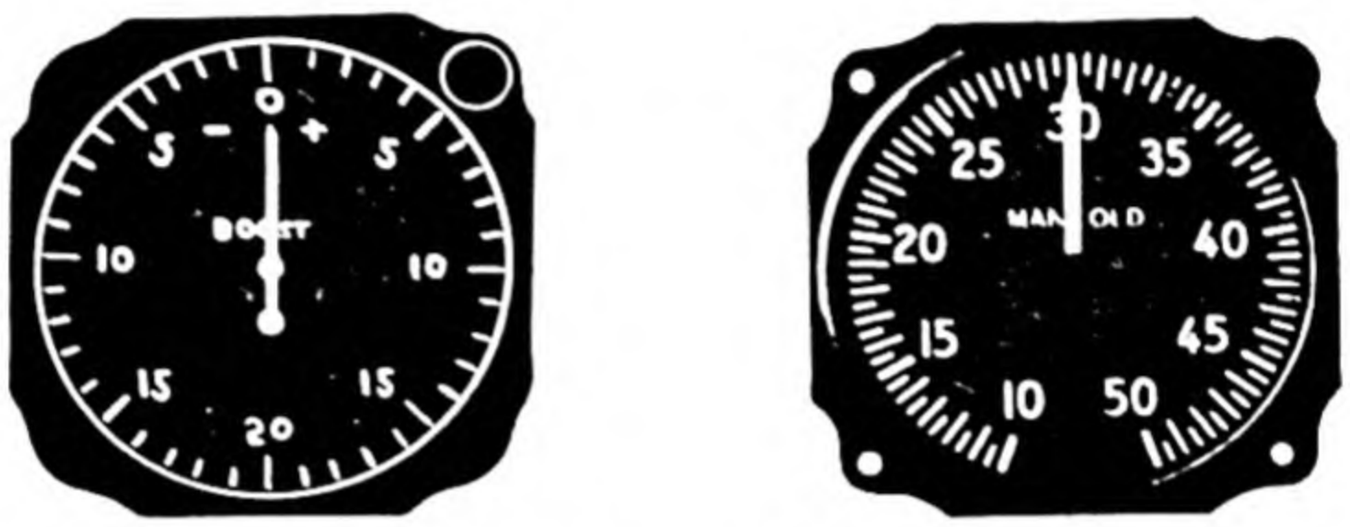


Fig. 32.—Boost and manifold pressure gauges

Two-speed Superchargers.

To return to the problem of the power wasted in driving a supercharger at ground level: the logical outcome is either some form of clutch that will allow the supercharger to remain idle when it is not wanted, or the use of a second low gear that will consume only a small part of the engine output. With an engine designed to withstand a moderate degree of ground boosting, and using high-octane petrol to avoid detonation, a low-gear supercharger pays for itself in increased power near the ground.

A typical modern gear-driven supercharger is equipped in this way with two gear ratios. With this mechanism the supercharger will turn at moderate speed in low gear, giving good power at low altitudes by the avoidance of unnecessary pumping. At greater heights a second gear is arranged to drive the blower at higher speed and maintain the permissible boost at greater altitude. The change from low to high gear is made at an altitude where both gear ratios give the same actual available engine power, but above which the low gear is less effective than the high. The gear change is usually operated by hydraulic means. The graph (fig. 33) shows how the power of the engine fitted with a two-speed supercharger varies with altitude.

A later development in gear-driven superchargers makes use of two stages of compression. When the air is compressed it is heated.

This represents an unavoidable loss of energy, but more serious is the drop in volumetric efficiency occasioned by feeding the engine with hot air. With a two-stage supercharger the problem is acute, and it is usual to cool the gases by passing them through a radiator situated either between the two stages, or between the final stage and the induction manifold. Such a combination provides a gain in horse-power over and above the single-stage blower, and gives the aircraft engine so equipped an even higher ceiling.

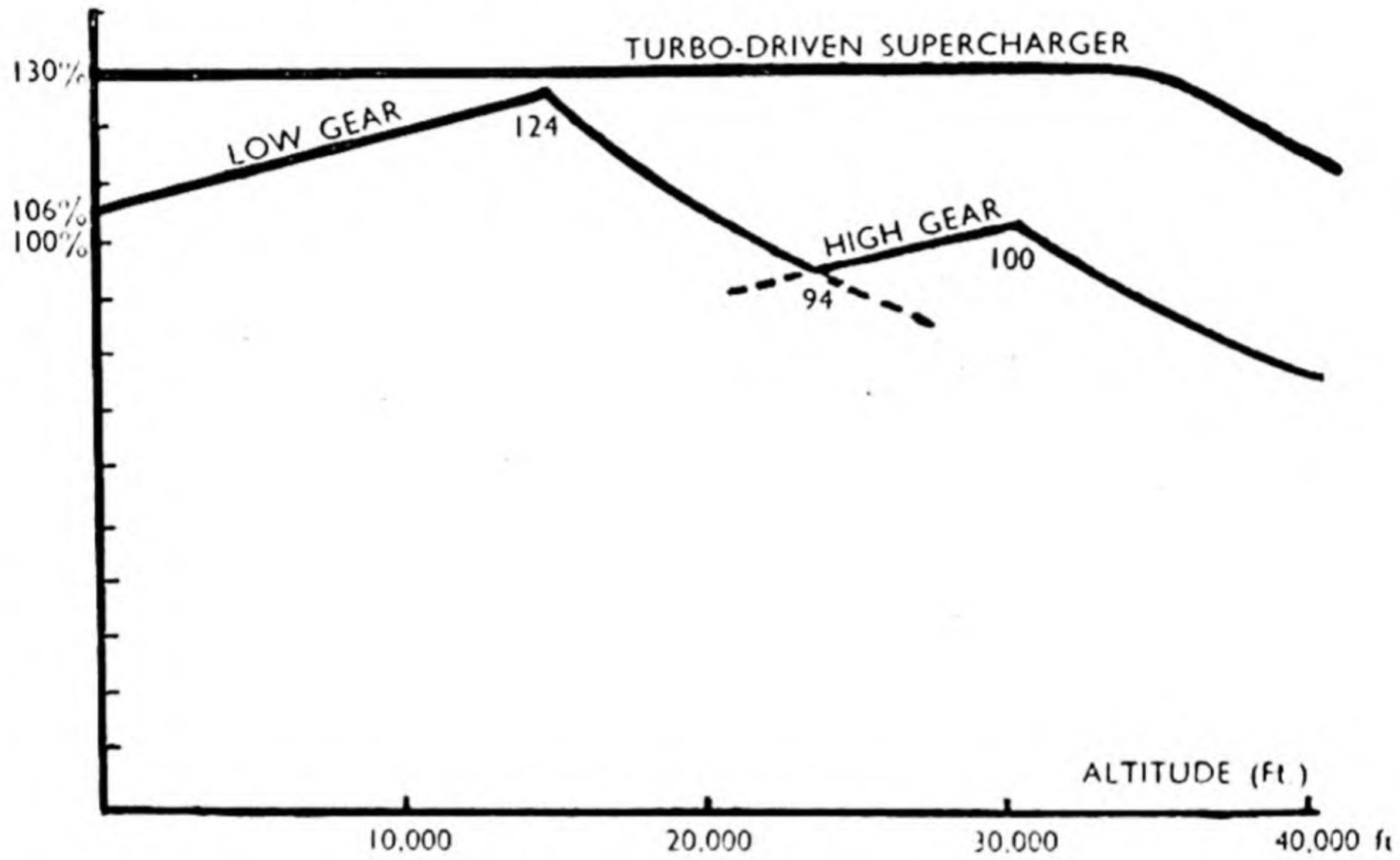


Fig. 33.—Comparison of 2-stage 2-gear with turbo-driven supercharger

Turbo-driven Superchargers (fig. 34).

The actual blower of a turbo-driven supercharger is of usual design; the novelty lies in the method used to drive it. Instead of being allowed to pass directly to the outside air, the exhaust gases are made to pass first through the blades of a turbine, the rotor of which is on the same shaft as the impellor.

In this way mechanical energy is derived from the hot exhaust gases as they leave, and very little power is absorbed from the engine.

Apart from the obvious advantage of using the waste gases as a source of power, there is another important advantage:

Each of the two gear ratios of a two-speed supercharger provides its maximum effectiveness at a given altitude. Between these two rated altitudes there is a drop in power due to one gear being too low and the other too high. The ideal way out of this dilemma would be to use a supercharger driven through a gear of infinitely variable ratio. The turbine of the exhaust-driven supercharger provides, in effect, just such an infinitely variable gear, for the speed of the blower may

be regulated by allowing more or less of the exhaust gases to escape directly to the air through a variable " waste gate ".

The turbine has, however, a variable speed characteristic of its own, which causes the change in speed to take place more or less automatically.

The speed of the turbine depends on the difference of pressure between the exhaust gases and the outside air. The greater the difference, the higher the speed of the turbine, and hence the greater the degree of compression by the supercharger.

So long as sufficient mixture is supplied to the cylinders the pressure of the exhaust gases will remain the same, whereas the pressure

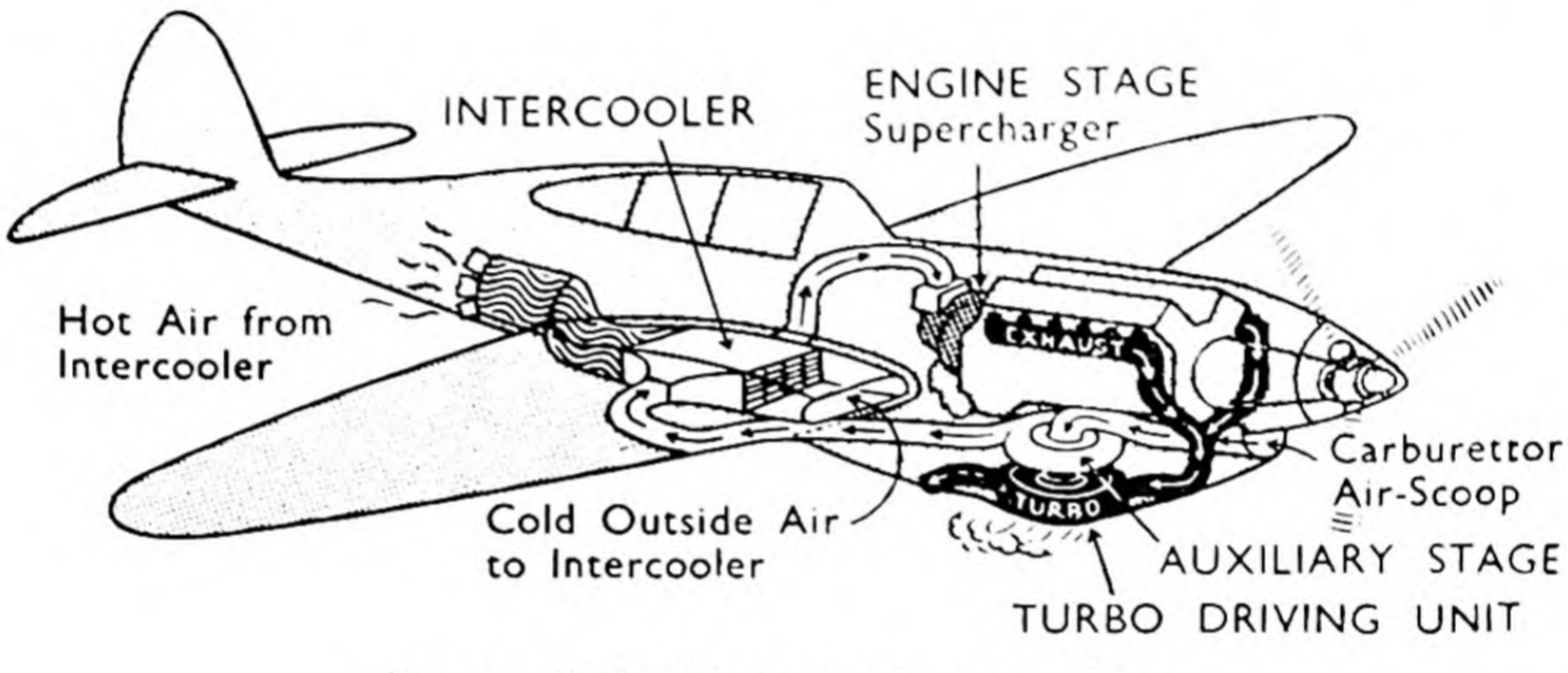


Fig. 34.—Turbo-driven supercharger installation

(By courtesy of General Motors, Detroit, Mich., U.S.A.)

of the outside air decreases steadily with increase in altitude. In consequence, as the aircraft rises higher and higher, the turbo-driven supercharger automatically picks up speed and provides the engine with a greater volume of air. The limit is only reached when the speed and temperature of the turbine rotor approach the safe limits for the materials used in its construction.

It is usual to employ two stages of compression, of which the second is gear-driven. An intercooler is placed between the two. Such a combination can be constructed to supply the engine with an almost constant weight of air up to very great heights. These results are reflected in the graph (fig. 33).

The turbo-supercharger is an outstanding innovation but it is not a " cure-all ". There are disadvantages to be weighed against the advantages, and, as usual in all matters relating to aircraft, the designer is faced with the problem of compromise.

The bulk and weight of the turbo-supercharger, with its exhaust

collectors and complicated plumbing, increase the difficulties of installation and limit its usefulness.

The expansion of the exhaust gases as they pass through the turbine greatly reduces their speed. It must be remembered that normally this speed is very high, and can be increased by specially shaped outlets to the exhaust manifold. The use of such " ejectors " at high altitude and high speed gives appreciable extra impetus to the aircraft. They are miniature jet-propelling engines. The use of a turbo-supercharger precludes any effective use of the exhaust in this way. Both are successful attempts to obtain more useful work from the exhaust gases before they escape, but apparently the designer cannot have it both ways.

Automatic Boost Control.

It has been earlier explained why it is necessary to close the throttle of a supercharged engine gradually as the aircraft descends. If this were left entirely to the pilot, he would need to be constantly adjusting the throttle lever and watching the boost gauge. With one more thing to think about, it would be indeed unusual if the engine did not occasionaliy suffer from " over-boosting ".

The automatic boost control is designed to relieve the pilot of the necessity for constant adjustment of the throttle lever, and to prevent the possibility of over-boosting.

Essentially the boost pressure itself is made to operate the throttle valve. The pilot selects the manifold pressure he requires by moving the throttle lever and the butterfly valve linked to it. The automatic control does the rest. If the aircraft climbs to greater altitudes, the throttle valve is slightly opened; if it descends, the valve is closed. Manifold pressure at the selected value is maintained automatically at all altitudes up to the rated altitude.

The principal component of the automatic boost control is the now familiar stack of aneroid capsules, subject in this case to the pressure existing in the induction manifold. A rise in manifold pressure causes the aneroid capsules to be compressed, and the stack shortens. This movement is made to bring about the necessary changes in throttle opening. The automatic boost control has nothing to do with control of mixture strength either for altitude or power, though it is often situated for convenience next to the carburettor.

QUESTIONS

1. (*a*) What causes the air to flow through the carburettor?

(*b*) "The volumetric efficiency of an unsupercharged engine decreases with increase in altitude." Define "volumetric efficiency" and explain this statement.

2. (*a*) Why does the power of an unsupercharged engine tend to fall off with increased altitude?

(*b*) In what way does the supercharger counteract this tendency?

(*c*) What cockpit instrument gives a direct measurement of what the supercharger is doing?

(*d*) What cockpit control is used by the pilot to control the degree of supercharging?

3. (*a*) Name two methods of driving the supercharger.

(*b*) Why is the engine with a supercharger able to give more power at great altitudes than the same engine without one?

(*c*) Why is the engine without a supercharger able to give more power at sea level than the same engine with one?

CHAPTER XIII

The Ignition System

ELECTROMAGNETIC PRINCIPLES. PERMANENT MAGNETS. INDUCED MAGNETS. MAGNETIC FIELDS. ELECTROMAGNETISM. ELECTROMAGNETIC INDUCTION. DYNAMOS AND MAGNETOS. CONSTRUCTION AND OPERATION OF THE MAGNETO. THE CONDENSER. THE DISTRIBUTOR. THE SAFETY SPARK-GAP. THE IGNITION SWITCH. DUAL IGNITION. MAGNETO TESTING. SPARK ADVANCE. SPARK RETRADING. THE SPARKING PLUG.

The combustible mixture in the cylinder is ignited by an electric spark across the points of the sparking plug. The Ignition System comprises the means for generating the electricity and distributing it to the right sparking plugs at the right time, and the plugs themselves.

ELECTROMAGNETIC PRINCIPLES

It is not the aim of this book to give a course in magnetism and electricity, but a brief résumé of the electromagnetic laws upon which the generation of the electricity in the ignition system depends is given here for those who wish to recall them. A more detailed treatment may be found in any standard textbook on electricity and magnetism.

Permanent Magnets.

The discovery by the Chinese about 2000 B.C. of a natural ore (lodestone) that pointed approximately to the North Pole when suspended was followed at later dates by the production of permanent bar magnets of steel that display the same property.

If the North-seeking ends (N-poles) of two such magnets are made to approach each other, a force of repulsion is found to exist between them. A N-seeking and a S-seeking end brought together in the same way show an equal attraction. In other words—like poles repel, unlike poles attract.

Induced Magnets.

It is well known that a permanent magnet will attract a bar of soft iron, and that both ends of the iron are equally attracted. It may be

shown that the soft iron, when near enough to the magnet to be influenced by it, has itself become magnetized. Such a temporary change produced by the proximity of another magnet is called *induced magnetism.* The nearer end of the soft iron is always an opposite pole, so that attraction, but never repulsion, results.

Magnetic Fields.

The region surrounding a magnet in which it displays its magnetic influence is of more importance than the magnet itself. The well-known experiment of placing a magnet under a sheet of paper and scattering iron filings over the top enables the nature of this *magnetic*

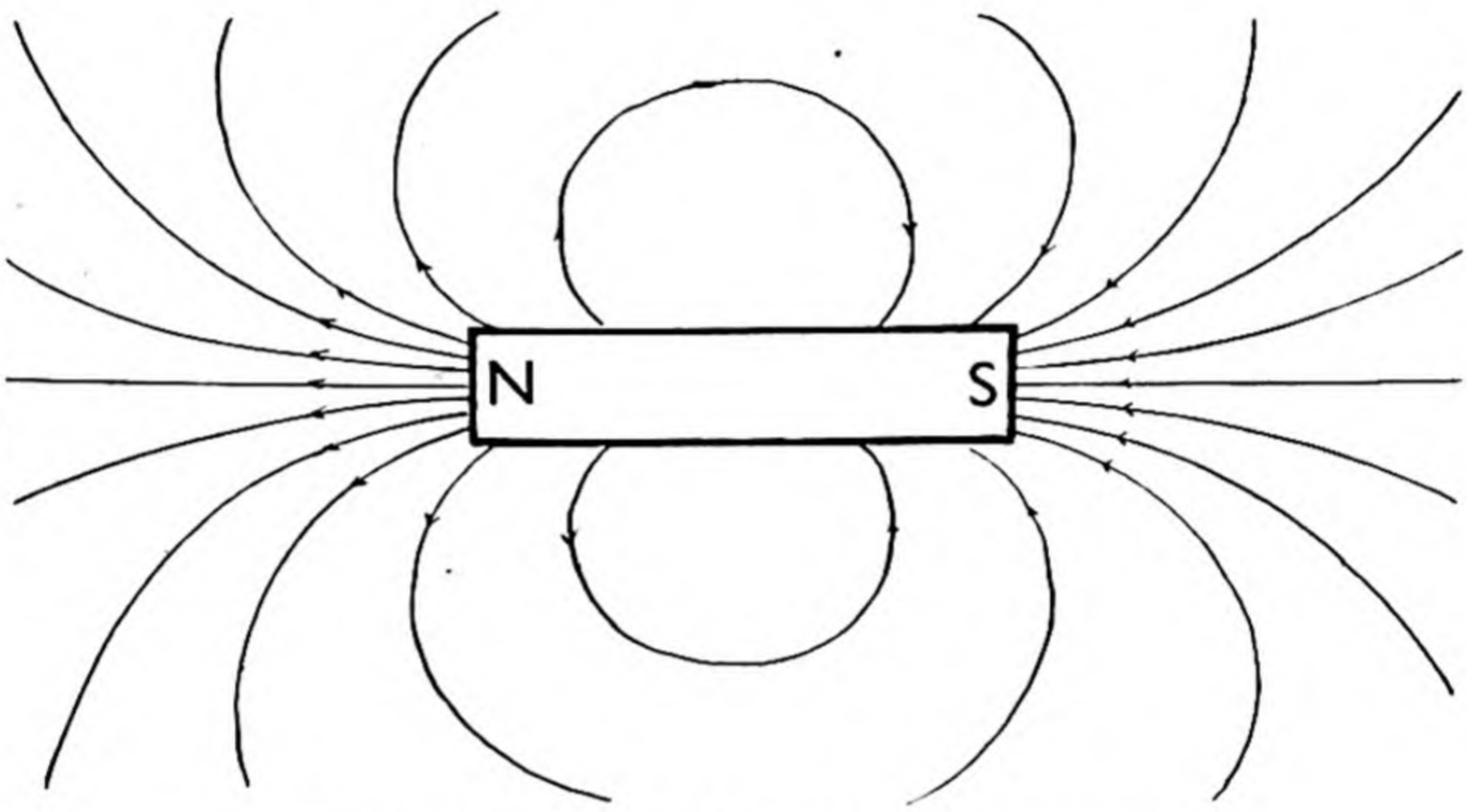


Fig. 35.—Magnetic field surrounding a magnet

field to be examined. The filings set themselves in definite lines, giving a grain to the pattern they display. These lines actually demonstrate visually the direction in which the magnetic influence acts, as shown in fig. 35. They are called *lines of force.*

Although lines of force have no physical existence in the sense that they may be seen or felt, it is often convenient to speak of them as though they were elastic bands, tending to shorten lengthways and push each other apart sideways. When this idea is applied to the field of magnetic force between two magnets, a convenient mental picture of the attraction and repulsion is presented.

Electromagnetism.

The existence of a weak magnetic field in the space surrounding a current-bearing wire (fig. 36) may be demonstrated by iron filings and other means. If the wire carrying the electric current is coiled

into solenoid shape, the resulting magnetic field, as shown in fig. 37, bears a very close resemblance to that of a permanent bar magnet.

The magnetic field surrounding a current-bearing solenoid is greatly strengthened by winding it on a core of soft iron. The sole-

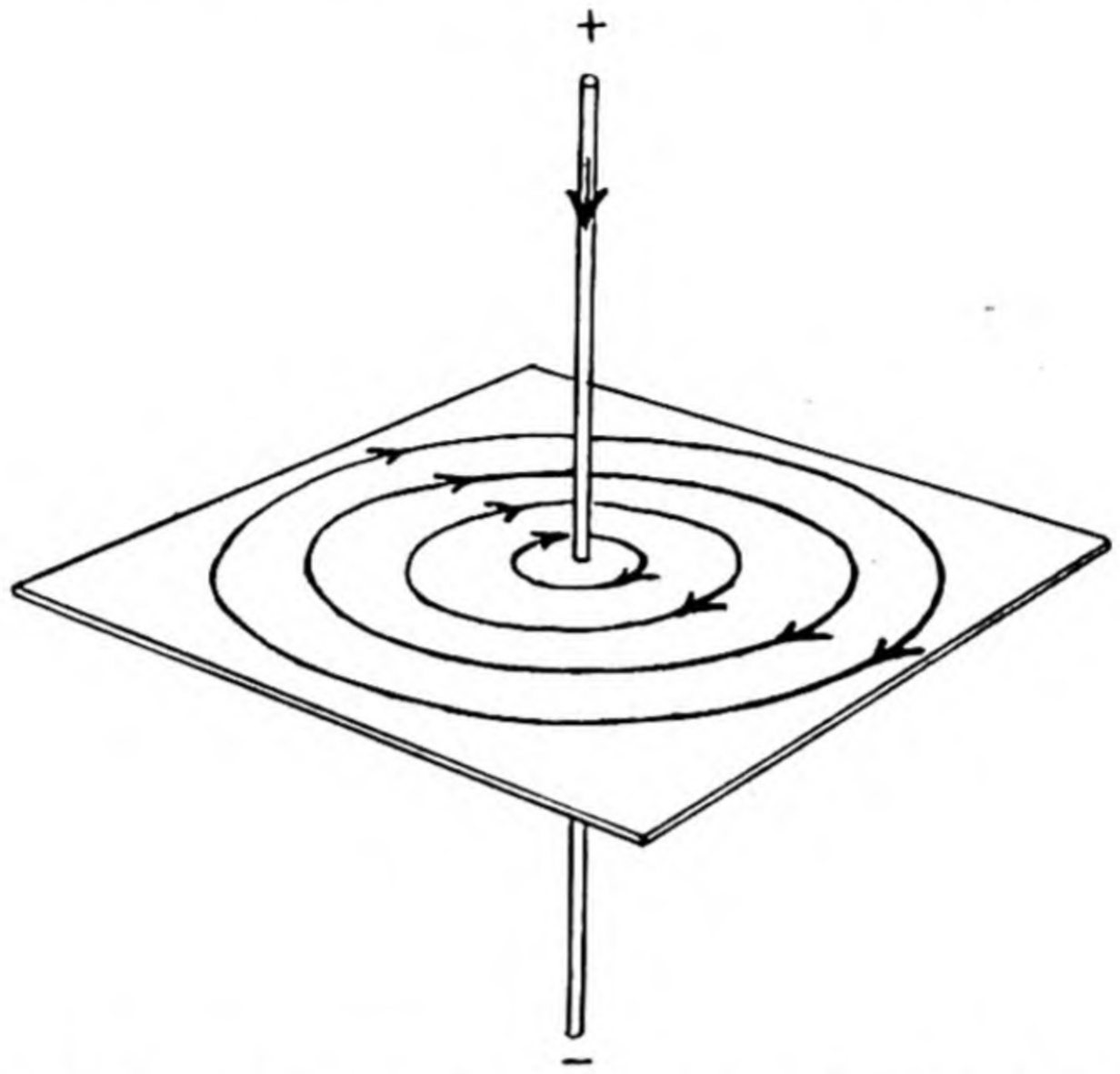


Fig. 36.—Lines of magnetic force round a current-bearing wire

noid induces magnetism in the soft iron in the same way as does a bar magnet. The resulting *electromagnet* is many thousand times more powerful than the solenoid alone, and its field may easily exceed

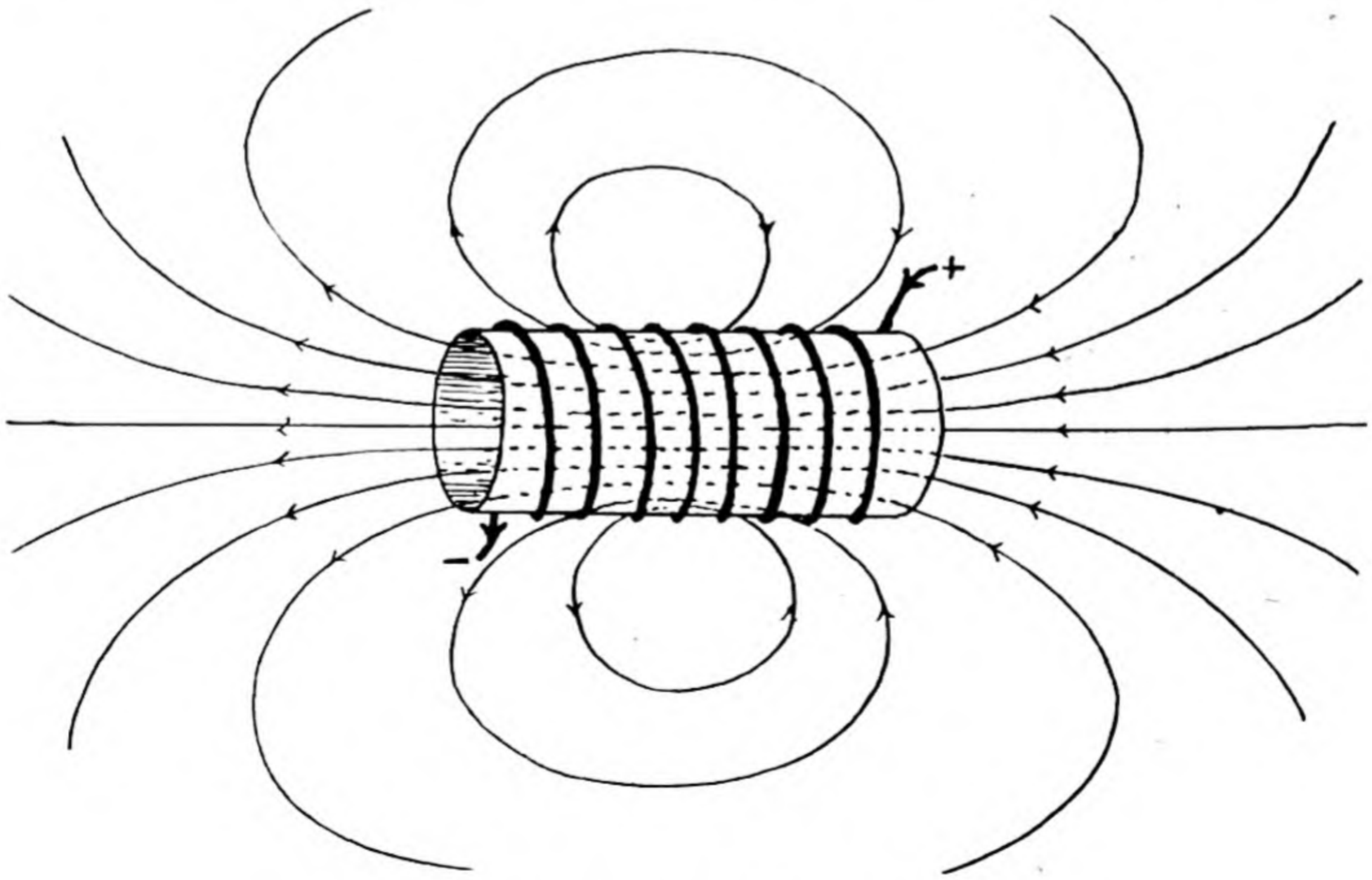


Fig. 37.—Magnetic field round a current-bearing solenoid

in strength that of a permanent bar magnet. Such electromagnets are used in industry for lifting scrap iron and other heavy steel or iron objects.

Electromagnetic Induction.

Once it was established that an electric current produces a magnetic field, experimenters sought to find out if the opposite were true, and if a current would flow in an electric conductor when surrounded by a magnetic field. To the scientist Michael Faraday went the honour of making the discovery that has revolutionized the industrial supply of electric power. Faraday's experiments demonstrated that an electric current may be generated in a conductor by a magnetic field, but *only when the lines of force of the field are made to cut the conductor*. This is called *electromagnetic induction*.

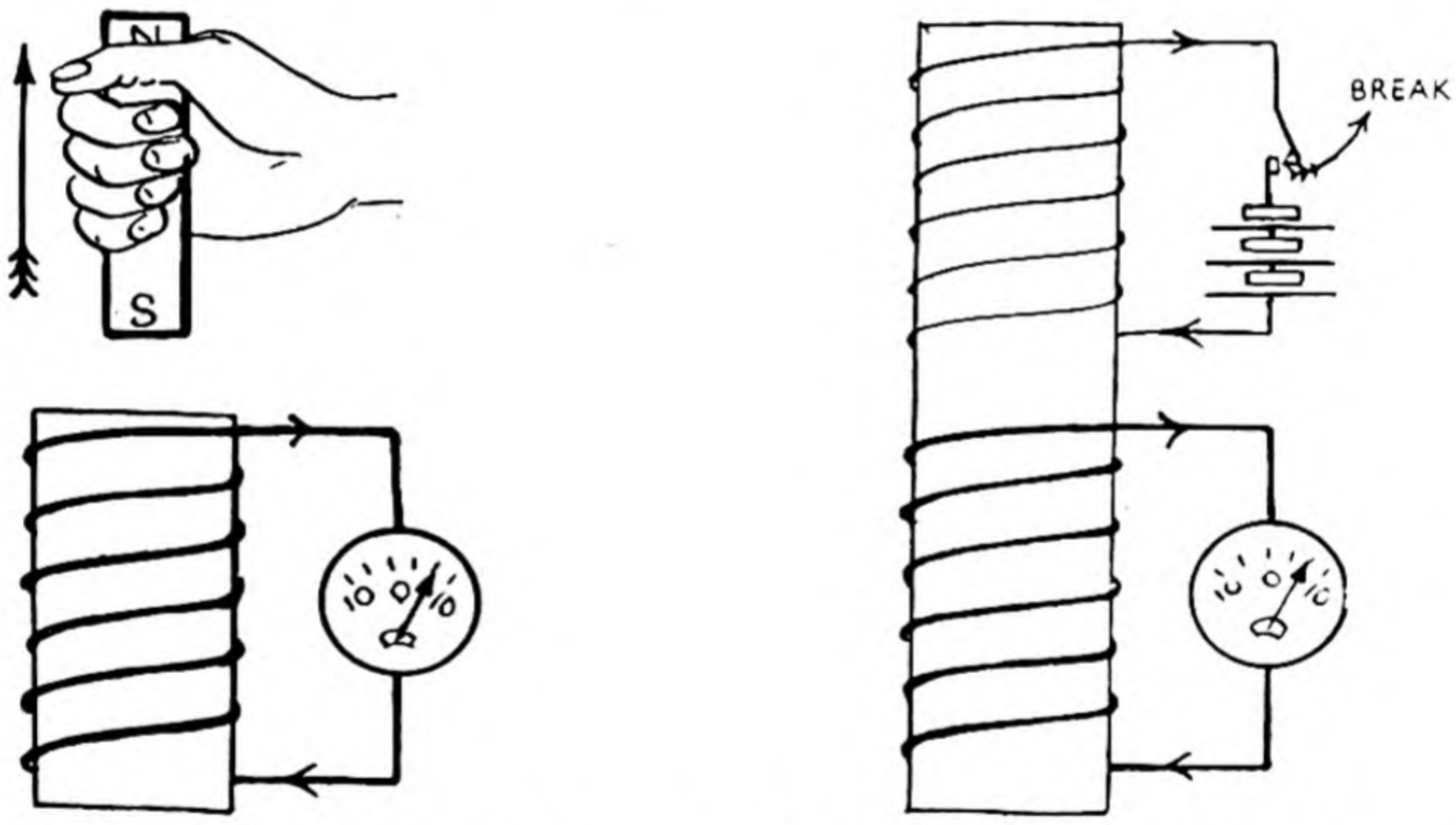


Fig. 38.—Current produced by a magnetic field cutting an electrical conductor

The magnetic field may be due to a permanent magnet, and the movement produced by hand, or another solenoid may be used. Both means are illustrated in fig. 38.

In the latter case it is sufficient to "break" the circuit of the current-bearing coil to make the lines of magnetic force cut the second coil. It is as though the lines shrank back into the current-bearing coil, as in a cinematograph picture of water ripples from a dropped stone when the film is run through the projector backwards. As they shrink and vanish, so they cut the other coil, and whilst the cutting continues, an electric voltage or pressure is generated between its ends. If the ends are joined, a current will flow. Again, a current

flows momentarily in the opposite direction in the second coil, as the circuit in the first is completed.

The names " primary " and " secondary " are used to distinguish the two coils.

The electrical voltage or pressure induced in the secondary coil may be increased in a number of ways. In the first place, winding the secondary on top of the primary coil is more effective than having them end to end. A very great improvement comes of inserting an iron core into the two coils: the primary becomes, in effect, an electro-magnet with consequently a stronger field. In fact it might be said

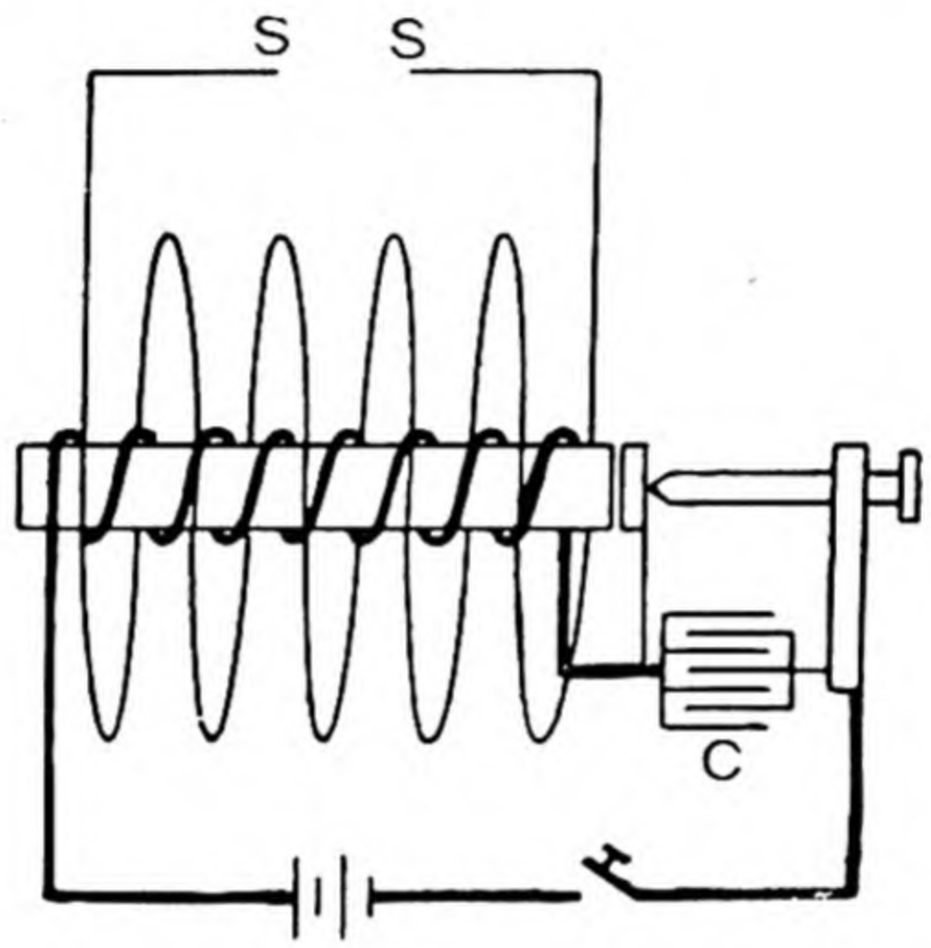


Fig. 39

that the secondary voltage is now due to the collapse of the magnetic field of the core, the primary serving the purpose of inducing magnetism in the core, and contributing only indirectly to the production of the secondary voltage. Lastly, the induced voltage may be increased by using a very large number of turns of wire on the secondary, and a comparatively few turns of wire on the primary coil.

If these conditions are fulfilled, a battery of only a few cells may be made to produce an electrical pressure large enough to force the secondary current across the resistance of a small air gap, and so produce a spark.

This is the principle underlying coil ignition. The arrangement used to produce the spark in this manner is almost identical with that used in the old medical or " shocking " coil, used in the laboratory under the name of induction coil when high voltages are required, and shown diagrammatically in fig. 39. The difference lies only in the method used to " break " the primary current. The induction coil employs a trembler similar to that on an ordinary electric doorbell,

whilst in the coil-ignition system a pair of contacts in the primary circuit are separated by a rotating cam driven from the engine.

Dynamos and Magnetos.

The production of electricity on a commercial scale makes use of Faraday's discovery of electromagnetic induction. A dynamo consists of a number of magnets rotated at high speed past coils of heavy copper wire wound on an iron core. If the coil is rotated and the magnets are stationary, the effect is precisely the same. In each case a magnetic field cuts an electric conductor.

The magneto is an electric generator or dynamo, inasmuch as it generates current by the relative movement of a magnet and a coil of wire. It is also something more, for whilst the ordinary dynamo is constructed to generate and deliver electricity at a desired voltage, the magneto does not deliver its current in the form in which it was originally generated, but converts it into a current of much higher voltage.

It does this in exactly the same way as in the coil-ignition system—by the use of a secondary coil of very many turns wound over the primary coil in which the electricity is first generated, and by " breaking " the primary circuit.

The magneto is therefore a self-contained combination of electrical generator and induction coil, and is independent of any extraneous source of electrical supply.

Whilst coil ignition is more popular with automobile engineers, the magneto is recognized as the standard fitting on aircraft engines. It is proposed, therefore, to devote the rest of this chapter to aircraft magnetos, and the components associated with them in the ignition system.

CONSTRUCTION AND OPERATION OF THE MAGNETO

The magneto may be thought of as consisting of four main parts, a magnet, the primary coil, the contact breaker, and the secondary coil. In the rotating-magnet type (see fig. 42) a current is generated in a primary coil of fairly thick insulated copper wire and comparatively few turns by the rotation of a permanent magnet. In the rotating-armature type (fig. 40) the permanent magnet is stationary and the coil rotates. In either case a magnetic field cuts the coil, and a low-voltage current is generated in it. This is the " dynamo " part of the magneto.

A secondary coil of very many turns of fine insulated copper wire is wound outside the primary. When the current through the primary winding is at its maximum, it is broken by the separation of a pair of contacts through which the primary circuit is completed, and in this way, as the magnetic field of the primary and its iron core collapses, a momentary high voltage is generated across the ends of the secondary coil. This is the voltage that forces an electric current across the points of the sparking plug and so causes the spark that ignites the charge in the cylinders.

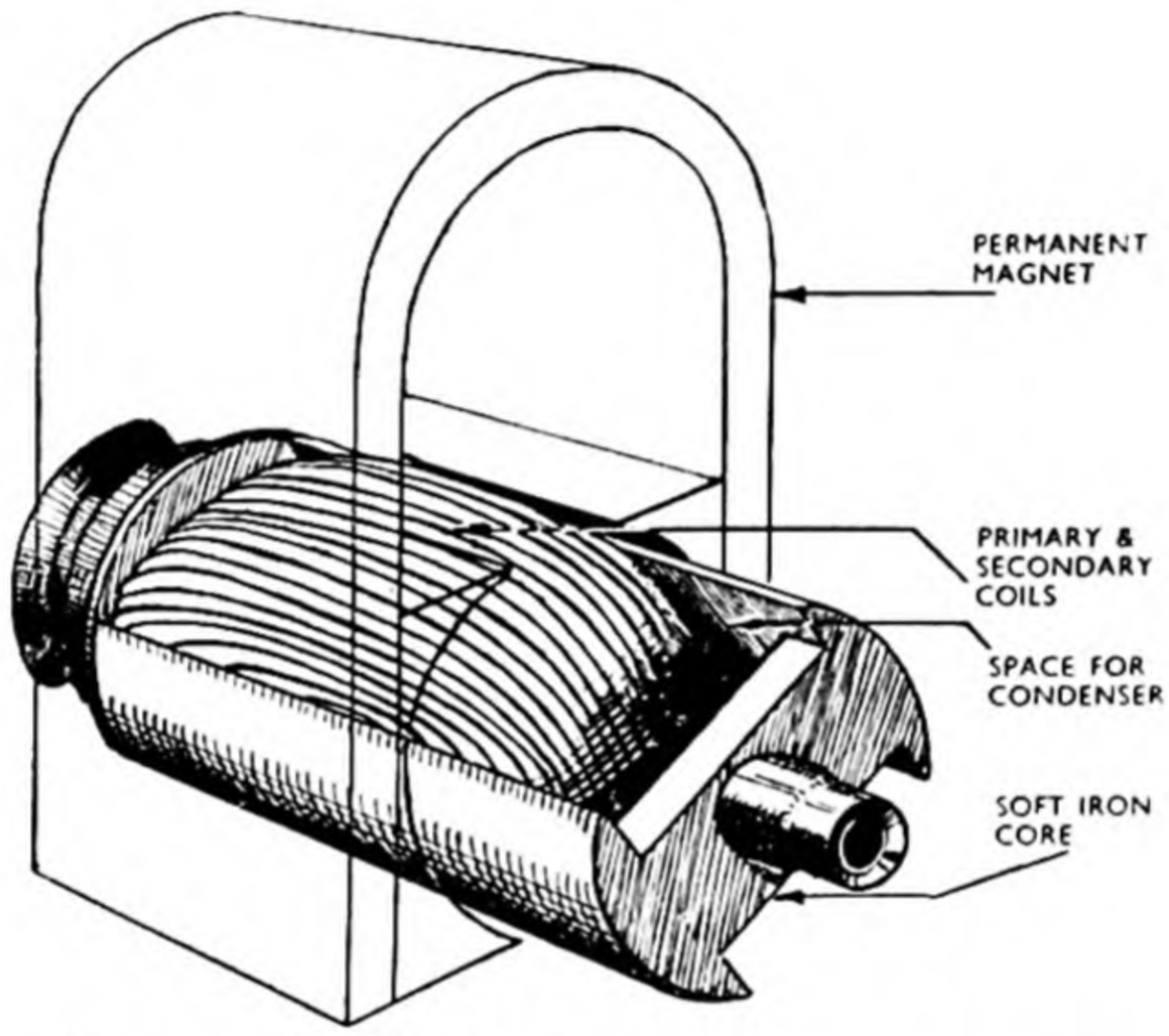


Fig. 40.—Essentials of a rotating armature magneto

The Condenser.

The contacts completing the primary circuit are normally held together by some form of spring, and are forced apart by the lifting action of a cam fastened to the rotating armature shaft. The possibility exists of arcing across these contacts when they are parted, and if this were to happen they would rapidly become pitted, and eventually so burnt as to cause failure of the ignition system. This is prevented by connecting an electrical condenser across the contact points.

The condenser serves another purpose. In order to obtain the greatest possible secondary voltage from the collapse of the magnetic field, it must change as rapidly as possible. It can be shown that a condenser of suitable size, connected across the points at which the primary circuit is broken, accelerates the collapse of the current and the associated magnetic field when the break occurs.

The Distributor.

The electrical voltage generated across the ends of the secondary coil is fed to a plug in each cylinder in turn by means of a rotating brush that passes by each of a number of contacts, each contact leading to one of the sparking plugs. This mechanism is called the *distributor*; it is built as part of the magnetic unit and is geared to the main armature shaft.

The Safety Spark-gap.

A feature of the magneto that is usually, but not always, present is the safety spark-gap. This is connected across the ends of the secondary winding for the purpose of safeguarding the secondary coil, and preventing damage to its delicate insulation, should a disconnexion or high resistance develop in the secondary circuit from broken leads, or fouled or faulty sparking plugs.

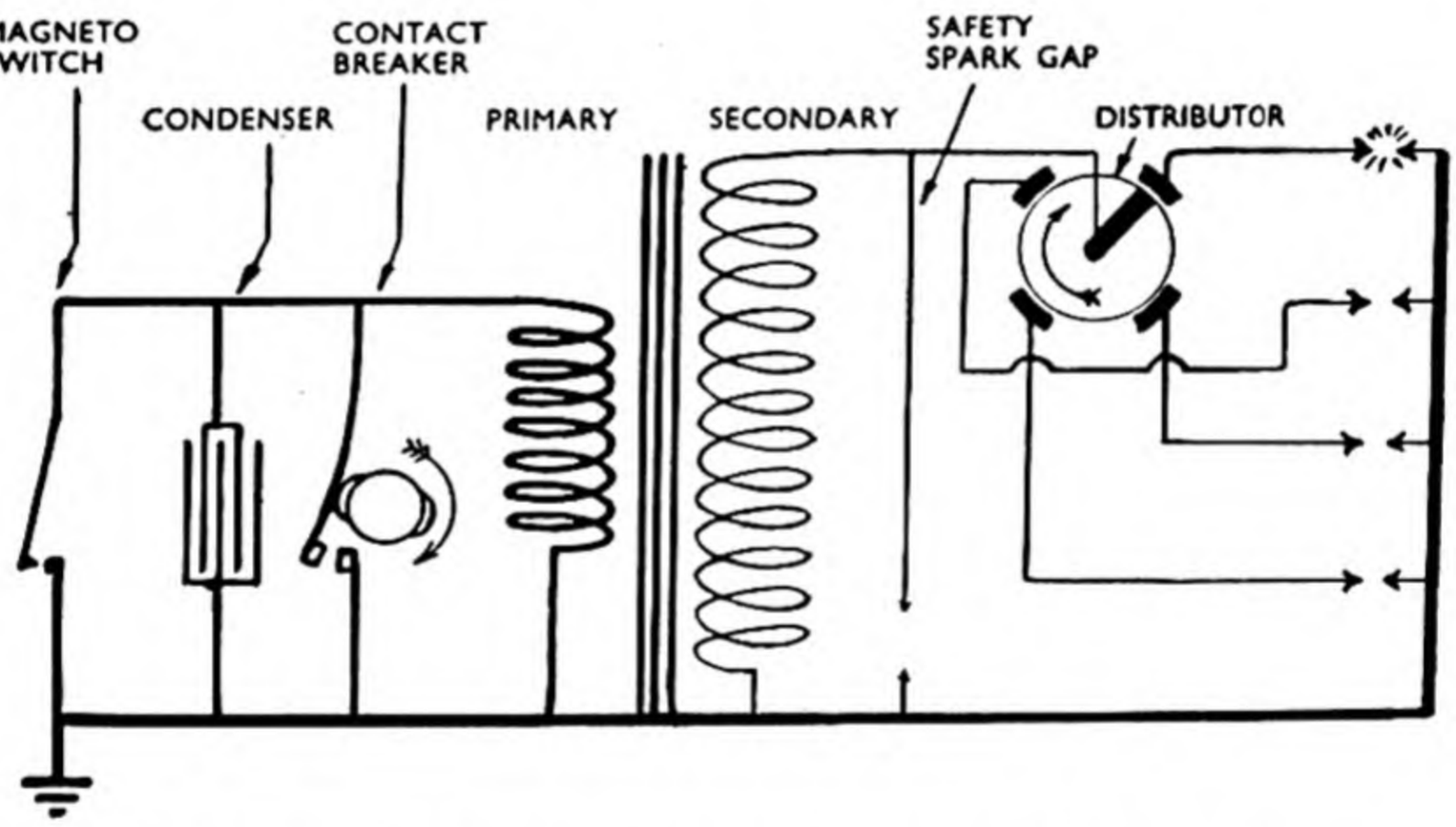


Fig. 41.—Ignition circuit for a 4-cylinder in-line engine

One side of the safety spark-gap, in common with the other parts of the magneto and the components of the ignition circuit generally, is "earthed" by being connected to the metal of the engine or aircraft frame. These form the return circuit and save the use of a second wire.

The magnetic circuit of the magneto and the primary and secondary coils, together with the contacts and contact-breaker cam, the condenser, distributor, and safety spark-gap, form one compact and reliable unit, capable of delivering, even in the case of a small engine of four cylinders, more than 4000 sparks per minute hour after hour.

Fig. 41 shows the complete ignition circuit. The use of the earthed return lead is to be noted.

Fig. 42 shows a magneto of the moving-magnet type.

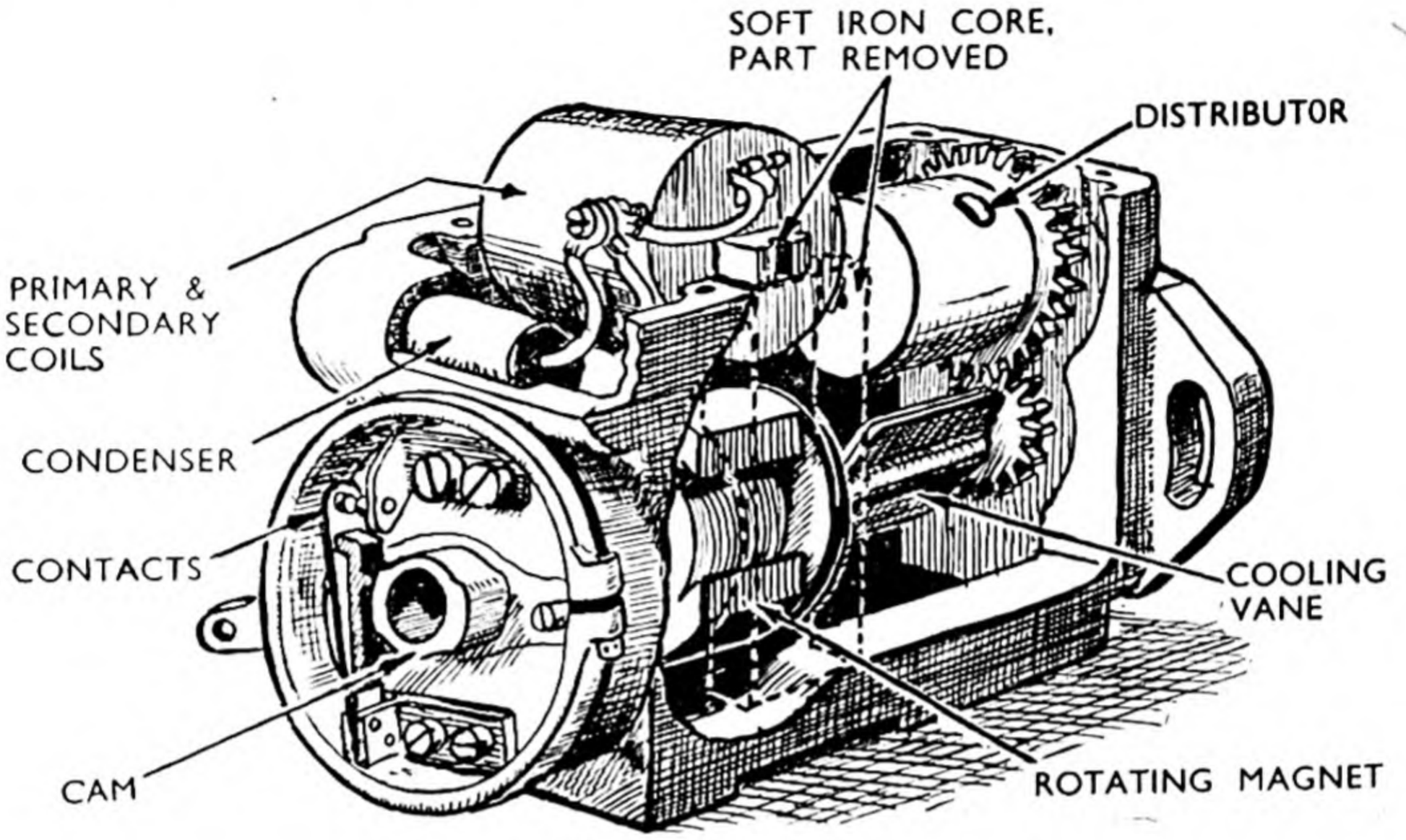


Fig. 42.—Small moving-magnet type magneto

The Ignition Switch.

An essential part of the circuit is the ignition switch situated in the pilot's cockpit and connected across the primary winding of the magneto. When the switch contacts are closed the contact breaker has no effect, for the primary remains complete, and the ignition system is then inoperative. This occurs when the switch is in the position marked " off ".

Dual Ignition.

The use of two independent ignition systems is a standard practice with aircraft engines. Each cylinder is fitted with two separate sparking plugs, and each one of a pair of plugs is energized by a separate magneto. The ignition circuit illustrated is therefore completely duplicated by a second similar system serving the same engine.

No doubt the original use of dual ignition was to safeguard against engine failure due to ignition faults, for, if one plug or set of plugs were to cease working, the engine would continue to fire on the other. There is, however, another advantage accruing from the use of two sparking plugs in each cylinder, for by starting the flame front from two points in the combustion chamber simultaneously, burning is more rapid and uniform, and detonation is less likely to occur. The

engine designer is therefore able to use slightly higher compression ratios, and obtain a greater thermal efficiency for his engine by use of dual ignition. It follows, of course, that the failure of one ignition circuit, when the engine is operating at full power, will immediately start detonation, the only immediate cure for which is to close the throttle.

Magneto Testing.

It is obvious that the pilot of an aircraft must make sure that both ignition systems are working properly, and it is therefore his invariable practice after the engine is warmed up to test each set of plugs in turn. To do this, the throttle is opened until the revolutions show that the engine is running at 75 per cent to 80 per cent of full power. When each magneto switch is put to the " off " position, the engine speed should not drop by more than a small specified amount, usually about fifty revolutions per minute, as indicated on the revolution counter.

Spark Advance.

The time taken for the mixture to burn in each cylinder does not vary very much under different running conditions, so that if the engine is turning over at a fast rate, the combustion must be started earlier than if the engine were turning over more slowly, in order that it may be complete at the same point in the stroke. The angular movement of the crankshaft between the spark and T.D.C. is called spark or ignition advance.

Sometimes provision is made for varying this spark advance to allow for different engine speeds, and the contact breaker is automatically rotated through a few degrees round the cam when the throttle is opened. It is usual enough, however, for the engine designer to find the best all-round position and to leave the spark advance fixed.

Spark Retarding.

When a small engine is being started by hand the crankshaft is turned over very slowly, and with normal timing, the combustion would be complete so far before T.D.C. as to force the piston down and rotate the crankshaft the wrong way. This is called *back-firing*, and the danger to the person swinging the propeller is obvious. To avoid this, the spark is often strongly retarded at low engine speeds by what is called an impulse starter. This is a mechanism incor-

porated in one magneto which, by momentarily arresting the movement of the magneto armature, delays the spark. In addition, by means of a spring, the magneto is flicked round sharply when it is released so that a good fat spark results. The other magneto, without an impulse starter, is not switched on until after the engine is started.

The Sparking Plug.

Aircraft sparking plugs operate under more severe conditions than automobile ones. Temperatures are so high that the plug points may become red-hot. Not only will this tend to give pre-ignition, that is, ignition before the proper time from the hot points instead of the spark, but the plug points may be burnt. Pressures are so high at the end of the compression stroke that very high voltages of the order of 10,000 to 15,000 volts are needed to force a spark across the gap, and this imposes severe strain on the insulation of the plug. Lastly, the plug is called upon to withstand the corrosive effects of " doped " or " leaded " anti-knock fuels.

The sparking plug is often considered the most important part of the engine, and considerable research has contributed both to its design and the materials of which it is made. Metals used for the points include tungsten, nickel-iron, nickel-platinum, and platinum-iridium alloys. The centre " live " point is surrounded by a number of earthed points, and the gap between them is of the order of 0·012 to 0·015 in.

The outer earthed part of the plug continues in the form of a flexible plaited steel-wire sheath that surrounds the insulating sleeve of which the live wire forms the core, and in this way interference with the aircraft radio receiver is prevented.

QUESTIONS

1. (*a*) Why are the switches turned off, one at a time, before take-off?

(*b*) Give two reasons for the use of two-ignition systems.

(*c*) What is the object of the condenser in the magneto?

2. (*a*) How is the low-tension current in the primary winding of the magneto transformed into the high-tension current in the secondary winding?

(*b*) What is ignition advance?

(*c*) When is ignition retarded?

3. (*a*) What is the purpose of the sparking plug?

(*b*) Is the magneto switch closed or open when the ignition system is switched off?

(*c*) What would be the effect of a short circuit of the condenser in the magneto?

(*d*) What is the purpose of the safety spark-gap?

4. (*a*) Draw a diagrammatic representation of the magneto and ignition circuit of the four-cylinder in-line engine, and label the parts.

(*b*) Give one possible order of firing the cylinders.

5. What is the purpose of the following:

1. The distributor?
2. The safety spark-gap?
3. The metal sheath to the sparking-plug lead?

CHAPTER XIV

Lubrication

FRICTION. HOW THE OIL LUBRICATES. THE BEARINGS. THE CYLINDERS. THE GEARS. THE VALVE-OPERATING MECHANISM. DESIRABLE PROPERTIES OF THE OIL. LUBRICATION SYSTEMS. PRESSURE FILTER AND SCAVENGE FILTER. OIL COOLER. OIL SUPPLY TO THE VALVE MECHANISM. WARMING-UP AND OIL TEMPERATURE CONTROL. TEMPERATURE AND PRESSURE GAUGES. SUBSIDIARY USES OF THE LUBRICATION OIL.

Friction.

A resistance is always offered to any attempt to move a block of metal with a smooth surface over a smooth metal plate, and this resistance is called friction. A force must be exerted to overcome it, and energy expended, if relative motion is to be maintained between the surfaces. If friction exists between the various moving parts of an engine, some of the mechanical energy that should reach the driving shaft is used instead to do work against frictional forces, and, of course, this means loss in power.

The energy so diverted reappears as heat, and if no steps were taken to reduce the friction between the rubbing parts of an aircraft engine, so much heat would be developed that high temperatures would soon cause sticking or seizing of the surfaces in contact.

Even if this did not occur damage to the surfaces would result, and the scratching and wear would roughen the surfaces so that friction would increase and matters tend to deteriorate progressively.

Examination of the apparently smooth surfaces under a powerful microscope shows them to be covered with minute points and pits. These are the hills and valleys that, by interlocking, resist motion, generate heat, and destroy the surface: this is the source of friction.

By separation of the metal-to-metal contact with a layer of oil (fig. 43), the hills and valleys are no longer allowed to interlock (fig. 44), and the friction is reduced to very small proportions. That which remains is due to internal friction in the liquid between the surfaces. The layers of oil slide over each other in the same way as playing cards in a pack when rubbed between the hands. This "liquid friction" is very small compared with the "solid friction" without the oil.

The *primary function* of lubrication is therefore to prevent metal-to-metal contact, thereby reducing friction. In this way more power is made available from the engine, less heat is generated, and damage to the surfaces is avoided.

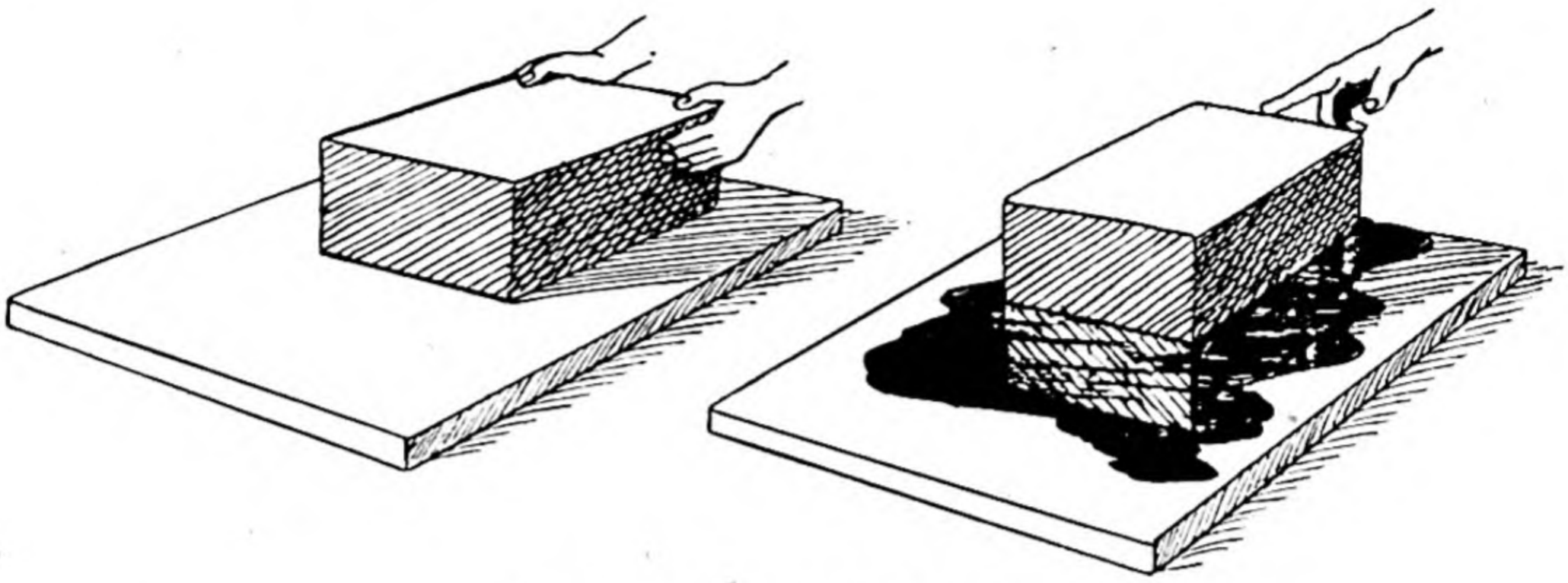


Fig. 43.—Effect of oil on friction

The oil performs a number of *subsidiary functions* besides. It seals the contact between the piston rings and the cylinder walls; it aids the main cooling system by carrying away heat from the bearings and gears; it helps to remove dirt and sludge from the cylinders and other parts of the engine; it helps to prevent corrosion. It is no wonder that efficient lubrication is essential to the successful operation of the aircraft engine.

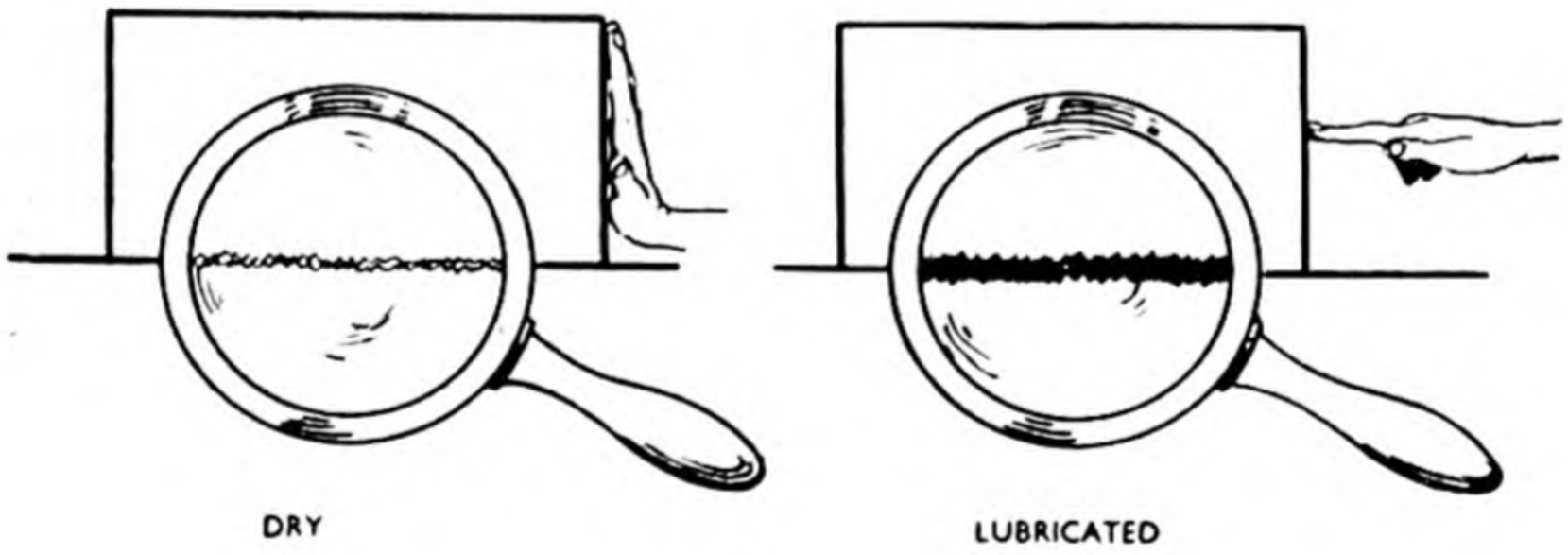


Fig. 44

How the Oil Lubricates.

The parts of the engine to be oiled are: the bearings, the cylinder walls, the gears, and the valve-operating mechanism.

The Bearings.

The oiling of any bearing is interesting. When a shaft is at rest in its bearing, the actual surfaces are in contact, but when the shaft begins to move, a wedge of oil is forced in front as it rotates. This

wedge begins to lift the shaft up from its bearing so that, when running, it is supported on a thin film of oil, as in fig. 45.

The choice of a suitable oil is not easy, for a number of factors must be considered. The oil must not be too thick or " heavy ", or the liquid friction will be unnecessarily great; but on the other hand, if it is too thin or " light " it escapes too easily from the ends of the

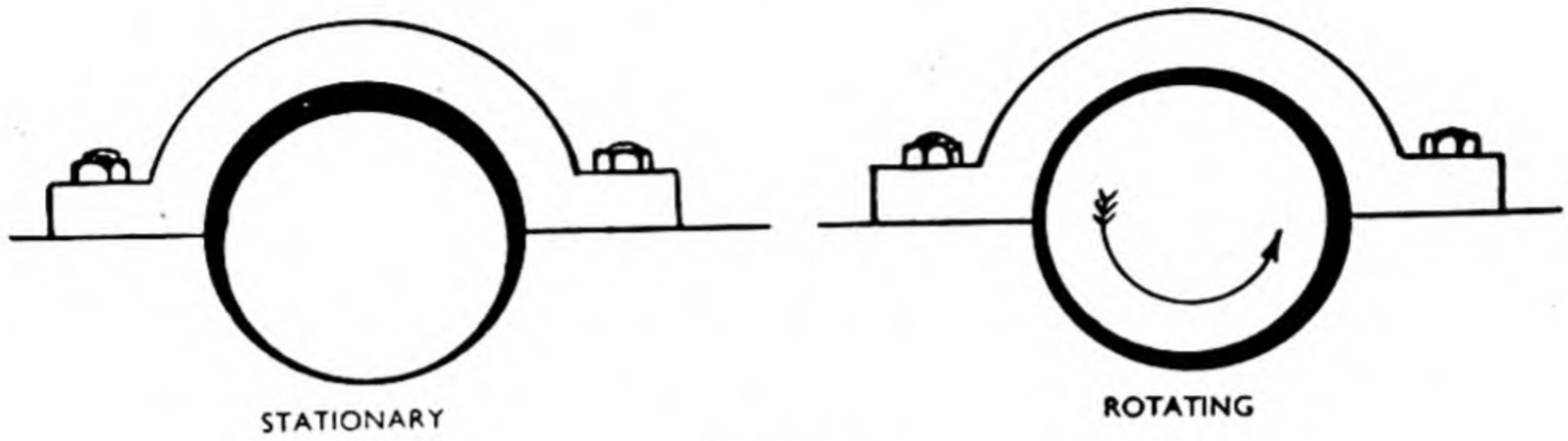


Fig. 45

bearing and the oil film is not maintained. The faster a shaft is moving the lighter the oil can be, but since it thins out as the temperature rises it must not be too thin when cold. The viscous nature of the oil when cold makes adequate lubrication of the engine difficult when it is being started, and special means are employed to overcome this difficulty.

The Cylinder.

In the cylinders other problems arise. The oil must have sufficient chemical stability to withstand high temperatures without chemical decomposition or oxidation. Chemical combination of the oil with the oxygen in the air (oxidation) or with the impurities in the oil from the wear of metal parts will form sludge.

One result of this sludge is to make the piston rings stick to the piston. This not only prevents the rings from sealing the gap between the piston and the cylinder, so that loss of compression and power will result, but the oil film is not spread over the cylinder and excessive wear and even scoring will occur.

The difficulty of preventing oil from oxidizing recurs in an acute form in the crank case. The crank case is filled with a fog of small oil droplets. As much as a gallon of oil may exist in the crank case in this form, and the extremely large surface area thus exposed to the air makes the prevention of oxidation one of the major problems for the oil refiner.

Returning to the cylinder, the action of the scraper piston rings will leave only the thinnest film on the cylinder walls. The ability of the oil to maintain this film even at high temperatures is another

desirable property of the lubricant, and is variously referred to as film strength, tenacity, adhesiveness, oiliness, &c.

The Gears.

As for the gears, the metal-to-metal contact is prevented here in the same way as with bearings, by the formation of an oil wedge where the gear teeth would come in contact. Since, however, the teeth are in contact over an area so small as to be almost a line, so that very high pressure results, the tenacity of the oil is here of paramount importance.

The Valve-operating Mechanism.

Various ways of leading the oil to the push rods and rocker arm are employed. These will be dealt with later (p. 175).

Desirable Properties of the Oil.

The ideal oil would have the following properties:

1. When cold it would flow perfectly freely.
2. When hot it would flow no more freely than when cold.
3. It would be chemically stable even at high temperatures.
4. It would separate quickly from solid impurities and from water.
5. It would have infinite ability to resist breakdown of the oil film.

It is impossible to have both (1) and (2) at once, for *the viscosity of an oil changes very quickly with change of temperature.* Some compromise must be made, and the operating temperature of the oil kept within fairly narrow limits.

When the extraordinarily severe tests to which the oil is subjected in the aero-engine are considered, it must be admitted that the oil at present in use has come a long way along the road to the ideal. The pilot, for his part, must see that the specified oil is used and that the regulations for warming-up and normal operation are strictly adhered to.

LUBRICATION SYSTEMS

It is now possible to see how the oil is taken where it is wanted in the engine. One method of lubrication would be to go round the bearings with an oil-can and drop oil into holes provided for the purpose. This is the method used for oiling some engines, but it is not good enough for the aero-engine: it is not only inefficient but wasteful.

Much of the oil is lost and dirt enters the holes in the bearings. An aero-engine lubricated like this would not run for five minutes before some of its bearings became too hot.

The aero-engine is lubricated by pumping oil where it is required. That escaping from the ends of the bearings is carefully collected, filtered and used again.

The crankshaft of the engine is hollow to save weight, and is used as a channel for the oil, which is forced by a pressure pump through small holes and grooves in the bearings. The oil escapes from the ends of both sets of bearings and is flung off in the form of a fine spray that effectively bathes the connecting rod, gudgeon pin, and cylinder with oil. The oil then drains down to the sump, which is usually the crankcase, and is then pumped round into circulation.

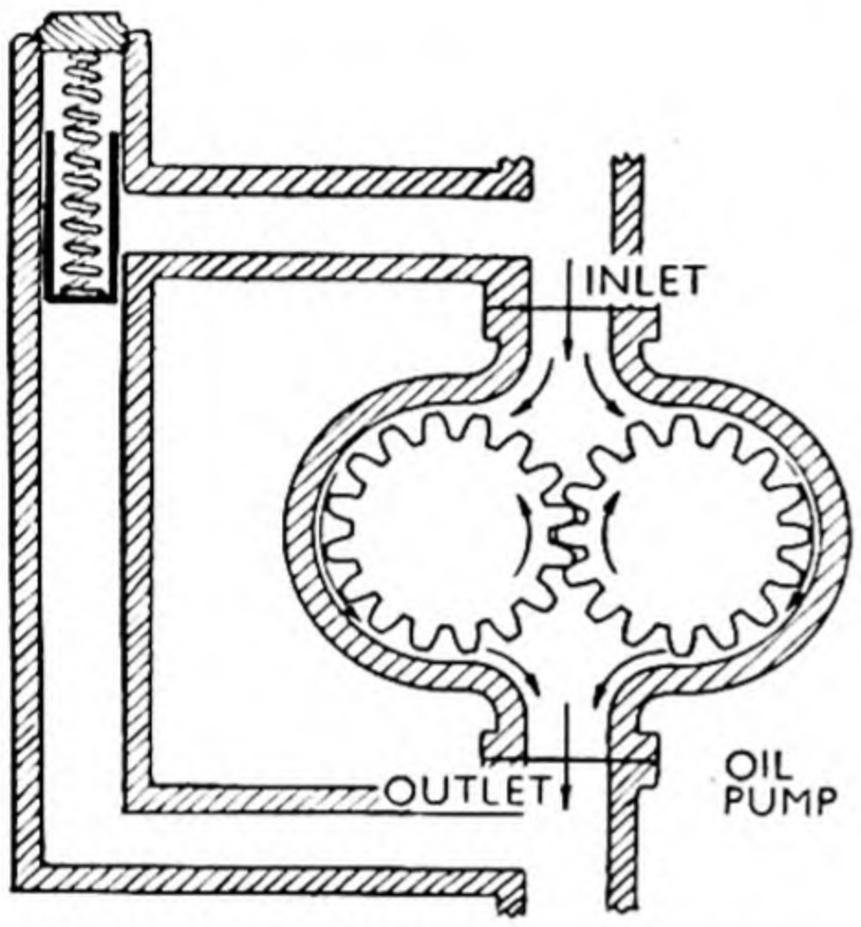


Fig. 46.—Pressure pump with relief valve

In some small engines the sump is also the oil reservoir, and this is called the *wet sump system*. In most engines, however, the *dry sump system* is used, when the oil is pumped out of the sump as fast as it collects by a *scavenge pump*, which returns the oil to an outside tank. There are therefore two pumps, the *scavenge pump* and the *pressure pump*. Both pumps are of similar construction and are often housed in one unit and driven together, but the scavenge pump is always bigger than the pressure pump, and is as a rule about twice the capacity. This is to ensure that there is no accumulation of oil in the crankcase which would give rise to over-oiling of the cylinders. Moreover, a considerable quantity collects in the bottom of the crankcase when the oil that is present in the form of a fog settles, and this must be returned to the tank as soon as the engine starts again.

Since the pressure pump is driven directly from the engine, the rate at which oil is forced through the engine would vary, and cause wide fluctuations in oil pressure. To avoid this, a relief valve is fitted which, although primarily designed to maintain a constant oil pressure, also acts as an escape outlet should any blockage occur in the oil circuit. Fig. 46 shows the usual gear type of oil pump used for both pressure and scavenge pump. The oil is carried round the outside of the wheels in the spaces between the teeth. The relief valve on the pressure pump is illustrated in this diagram in a simplified form.

The simplified oil system so far takes us from the oil tank to the pressure pump, then through to the engine crankshaft. After the oil has drained down from the cylinders to the sump, the scavenge pump forces it back to the tank. One or two details need to be added to complete this picture of the lubrication system.

Pressure Filter.

However careful the mechanic may be, the oil that is put into the tank may not be perfectly clean. A filter is therefore placed between the tank and the pressure pump; it is called the pressure filter.

Scavenge Filter.

There is an oil filter at the bottom of the sump to clean the oil before it is returned by the scavenge pump. This filter is called the scavenge filter.

Oil Cooler.

The temperature of the oil rises as it passes through the engine, partly owing to the heat generated by residual friction, but mostly owing to heat gained from the hot cylinders and warm engine parts to which heat from the cylinders has been conducted. Therefore, all aircraft engines but the smallest need some means of cooling the oil before it is returned to the tank, and this is achieved by taking the oil through the spaces between a number of copper tubes exposed in the airstream.

Oil Supply to the Valve Mechanism.

Various means are used to lubricate the push rods, camshaft and rocker arms. If the camshaft is in the crankcase, then it is adequately oiled by the splash, though in some cases oil from a *pressure-reducing valve* on the delivery side of the pressure pump is taken along the hollow centre of the camshaft and escapes from the camshaft bearings to oil the associated parts as a spray. This method of camshaft lubrication is used in Merlin engines. A triple relief valve serves to regulate the pressure of the oil that leaves the pressure pump, firstly at 150 lb./sq. in. for operation of the variable-pitch propeller, secondly, for the main bearings and gears at 70 lb./sq. in., and the lowest pressure of about 6 lb./sq. in. for the camshaft and other auxiliaries.

In the inverted in-line engines the sump is formed by the extension of the ends of the cylinders into the crankcase. The rocker arms are the lowest part of the engine now and are completely enclosed in a casing kept half full of oil (by drainage from the oil mist in

the crankcase down the push-rod casing), so that the rocker arms dip into the oil when moving.

The rocker arms of radial engines are usually lubricated by grease injected from a grease gun.

A complete lubrication system is shown in fig. 47.

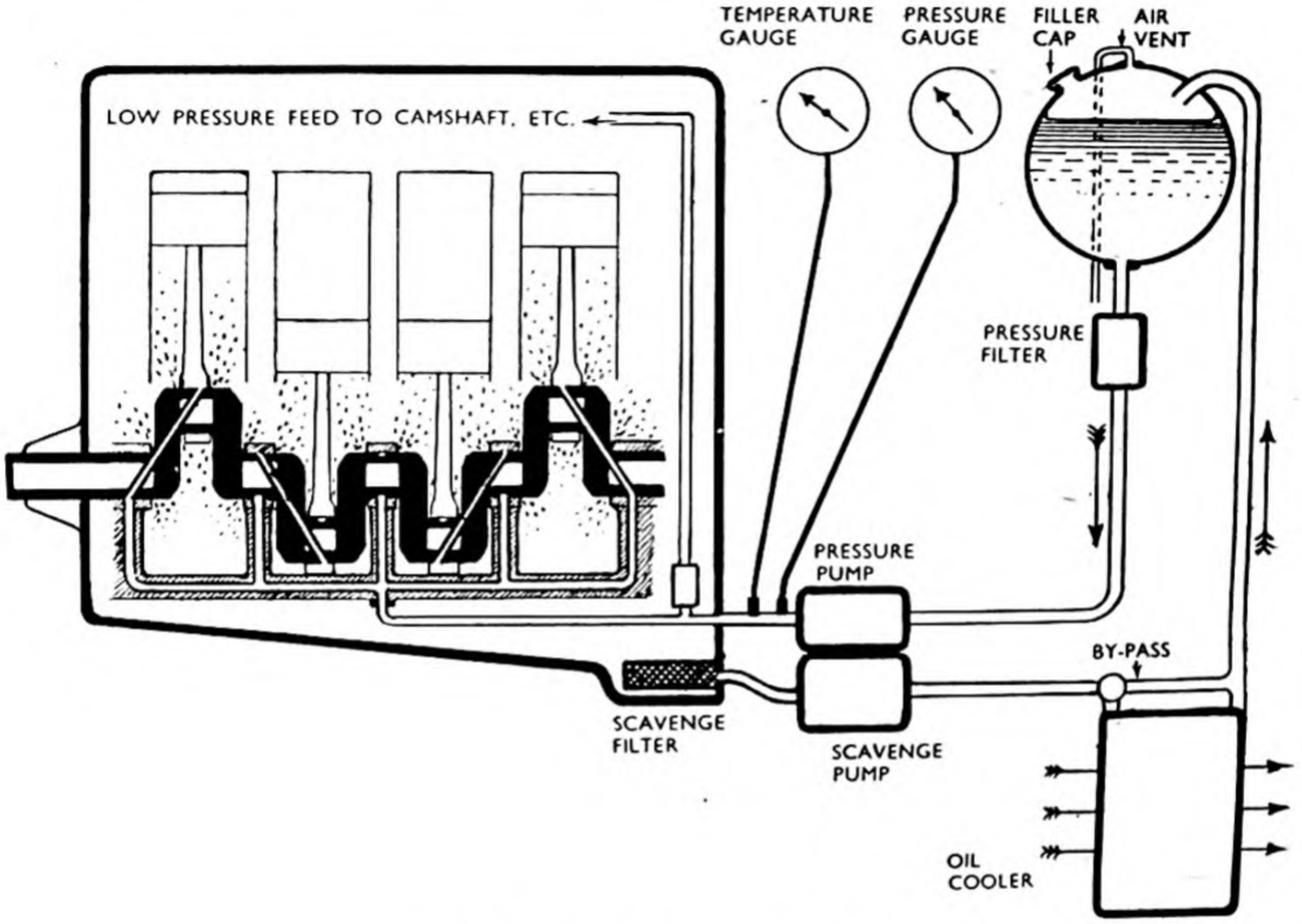


Fig. 47.—A lubrication system

Warming-up and Oil Temperature Control.

When the engine is started, the oil is cold and therefore stiff and treacly, and will not flow easily. Warm oil must begin to circulate as quickly as possible and bathe the piston and cylinder; otherwise the partially evaporated petrol in the cylinders washes the oil from the surface and they are damaged. There are four different ways of doing this:

1. A by-pass valve may be used to take oil from the scavenge filter directly to the tank without its passing through the oil cooler.
2. The oil cooler may be blanked off from the airstream, by means of a shutter at the rear of the cooling duct.
3. Only part of the oil in the tank may be used at first, so that it warms up quickly. In this device, the main supply must pass through a cylinder perforated with small holes inside

the main tank, and called the *hopper tank* (see fig. 48). Thus, at first, only that small portion of oil within the perforated cylinder circulates through the engine, for the oil is too viscous to flow through the holes in the hopper tank. As the oil in the main tank becomes warmer it flows through the holes easily and joins the circulation.

4. The oil-dilution system is being increasingly used, for it gives a very quick get-away to a fighter aeroplane. For three or four minutes before the aeroplane is put away, petrol is pumped into a portion of the oil, isolated from the rest of the tank. The engine starts quickly on this thinned-out oil, and as soon as the petrol that is mixed with it is evaporated the oil returns to normal. Incidentally, it keeps the oil passages cleaner. The effect of pumping thinned-out oil into the engine lasts for three or four days.

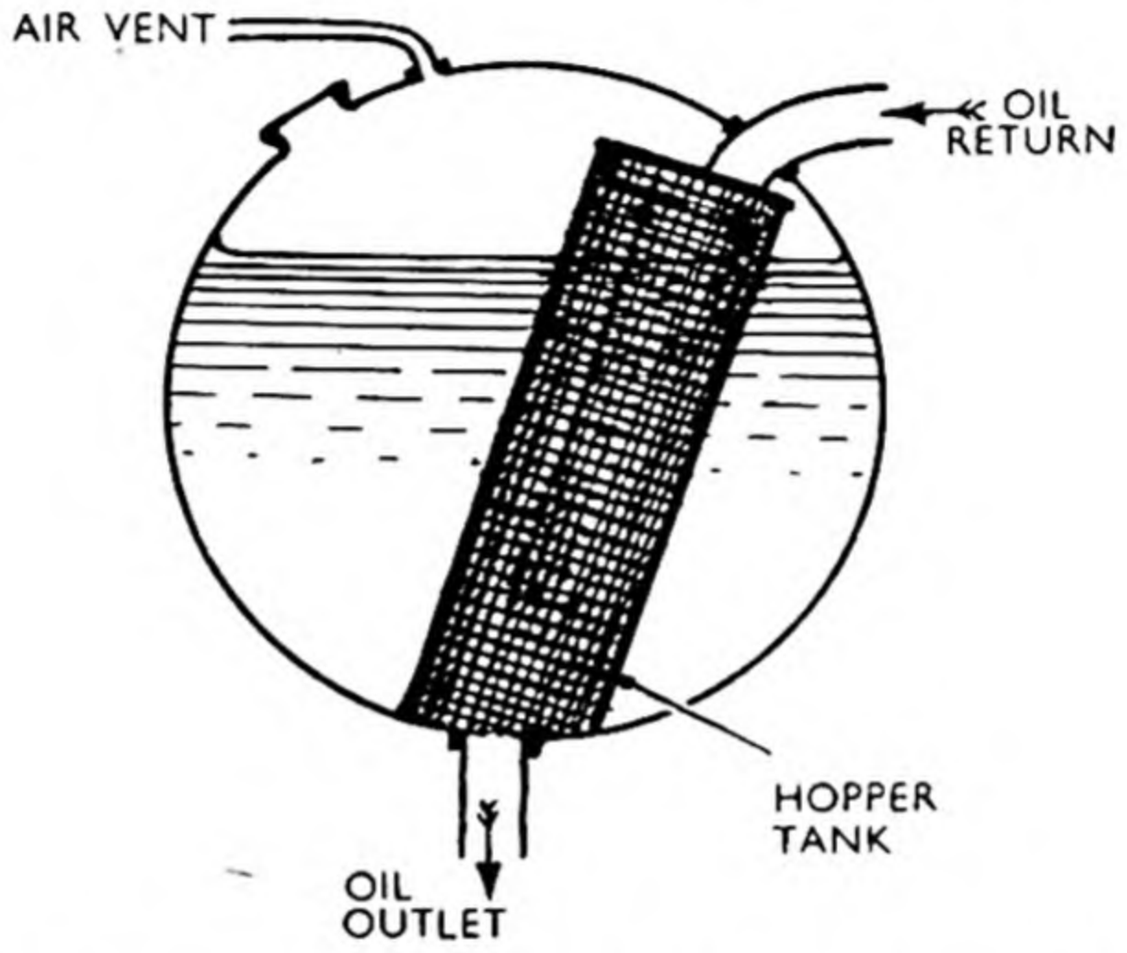


Fig. 48.—When cold, only the oil in the hopper tank circulates

The by-pass valve and the shutter behind the oil cooler provide means whereby the temperature of the oil may be controlled in the air. Sometimes the control is automatic and sometimes it is operated by the pilot.

Temperature and Pressure Gauges.

Gauges are fitted to the lubrication system. The pressure gauge measures the pressure of the oil as it leaves the pressure pump. This pressure is usually somewhere between 50 to 100 lb. per square inch, depending on the type of engine, and should not vary. The temperature of the oil is measured by a thermometer, usually as it enters

the engine. From the pilot's point of view these two gauges are very important. The pressure gauge is the first instrument to look at after the engine starts, to ensure that it is being properly fed with oil. In the air, the reading on the oil-temperature gauge must be kept within the proper limits, for if the oil is too cold it will not flow easily and the rate of circulation will be too slow, and if it is too hot it will escape too rapidly from the bearings and gears, and the oil film there may break down.

Lubrication has been dealt with in some detail because the proper running and the life of the engine will be governed largely by the intelligent care given to the lubrication system.

The parts of the lubrication system can easily be remembered, if the sequence is followed out logically from the oil tank—thus:

1. The oil leaves the tank and enters the *pressure filter* on its way to the
2. *pressure pump* with its *pressure relief valve.*
3. The high-pressure oil is forced into the *crankshaft*, and escapes therefrom to oil the *cylinders*, &c., by mist.
4. It drains down into the *sump*, and is immediately drawn off through
5. the *scavenge filter* by the *scavenge pump.*
6. On its way back to the tank the oil is cooled by the *oil cooler*, with possibly a *by-pass valve* for starting.
7. It only remains to add the *reducing valve* to the delivery side of the pressure pump and to take the oil that passes through this to the *camshaft*, and finally complete the picture with
8. the *pressure gauge* taken from the delivery side of the pressure pump, and the *thermometer* measuring the temperature of the oil.

Subsidiary Uses of the Lubrication Oil.

On its way to the tank the oil is often led through a jacket surrounding the carburettor, and may even pass through the butterfly or throttle. It then serves the very useful purpose of preventing the icing-up of the carburettor and helping to evaporate the fuel.

Engine oil is also used in the operation of some controllable-pitch propellers.

QUESTIONS

1. (*a*) What is meant by the dry sump system of lubrication?
(*b*) What special function does the oil fulfil in the cylinder?
(*c*) How is the cylinder usually oiled?

2. (*a*) Make a list of the component parts through which the oil passes on its way to the engine from the tank, and another list of the component parts through which it passes on its way from the tank to the engine.

(*b*) What cockpit instruments are connected to the oil system?

(*c*) In what ways may the oil temperature be regulated in the air?

3. Name the two pumps that are generally fitted to the lubrication system of the aero-engine; say which is the larger, and give the reason for your answer.

4. Why are the following components fitted to the lubrication system:

1. The oil radiator?
2. The scavenge filter?

5. (*a*) What is the purpose of the oil-pressure relief valve?

(*b*) What would be the first sign if the oil-pressure relief valve were stuck open?

(*c*) What is " oil dilution " and what is it used for?

6. (*a*) Name three purposes served by the oil in the engine bearings.

(*b*) Sketch an oil pump and mark the direction of rotation of the parts and the direction of the oil flow.

7. (*a*) Why must the engine be warmed-up after starting before full throttle is used?

(*b*) How are the big-end bearings oiled?

(*c*) How are the cylinders oiled?

8. (*a*) Why may the engine receive an insufficient supply of oil when first started?

(*b*) Indicate briefly three methods of ensuring that the engine *does* receive an adequate supply of oil very soon after it is started.

9. (*a*) What three objects are achieved by the reduction of friction?

(*b*) Name one additional function that the oil performs in the cylinders.

(*c*) Name one additional function performed by the oil in the bearings.

CHAPTER XV

Cooling

REASON FOR COOLING. AIR COOLING: CYLINDER-HEAD TEMPERATURES; METHODS OF AIR COOLING. LIQUID COOLING; CHOICE OF COOLANT. CHOICE OF COOLING SYSTEM.

Reason for Cooling.

It has been emphasized from time to time that the engine is a machine for turning heat energy into useful mechanical work, and that the aero-engine, like others of its type, only succeeds in converting in this way a proportion of the heat released by the combustion of the fuel. It will be remembered that about 35 per cent of the heat that the engine fails to convert into work remains in the exhaust gases. When the exhaust gases are ejected from the exhaust manifold, this heat is left in the wake of the aircraft, and it is lost as far as the aircraft's making use of it is concerned. In some aircraft part of this escaping energy is recovered and used for driving the turbine of the supercharger or, by means of the ejector exhaust, made to contribute directly to the propulsion. On the whole, however, the exhaust gases contribute most to warming the air behind the aircraft.

There remains about 30 per cent of unconverted heat that passes directly into the cylinder walls, cylinder head, valves, pistons and exhaust manifold. Some of this heat is radiated from the warm outer surface of the engine, and some, conducted along the connecting rods, is finally removed by the circulating oil; but this is not enough, and, unless there is some special means for dealing with the remainder, the engine will become too hot. As far as the theoretical thermal efficiency of the engine is concerned, the higher the temperature at which it operates the better, but a compromise is necessary, for at too high a temperature the oil fails to lubricate, and all the other symptoms of overheating appear: valve pitting, sparking-plug failure, pre-ignition, detonation, and in the end general mechanical failure. Heat must therefore be removed from the engine at a rate sufficient to keep the engine temperature down to safe limits, and the cooling system is responsible for this control of engine temperature. In a thousand-horse-power aircraft, about 20,000 B.Th.U., sufficient to boil more than 100 lb. of water, must be removed in this way every minute.

AIR COOLING

The cylinders of an air-cooled engine are made with broad fins which offer a large surface to the passing airstream. On the cylinder barrel they are machined out of the solid metal. The cylinder head, with its fins, is a casting from aluminium alloy of high thermal conductivity. As engines have become more powerful and the problem of cooling more difficult, the number of fins has been increased and their distribution modified to give more efficient cooling. The cooling area of a modern radial engine of 1000 h.p. lies usually between 150 and 180 sq. ft.

The usual arrangement of poppet valves in the cylinder head makes cooling of this part of the engine difficult. This is particularly unfortunate, as this is the hottest part of the engine. The cylinder head is therefore very heavily finned, especially around the exhaust valve.

Cylinder-head Temperatures.

Fig. 49 gives a general idea of the mean cylinder temperatures of an air-cooled engine. It will be noticed how much hotter the region of the exhaust valve is than any other part of the engine, with the exception of the exhaust manifold. The exhaust manifold presents

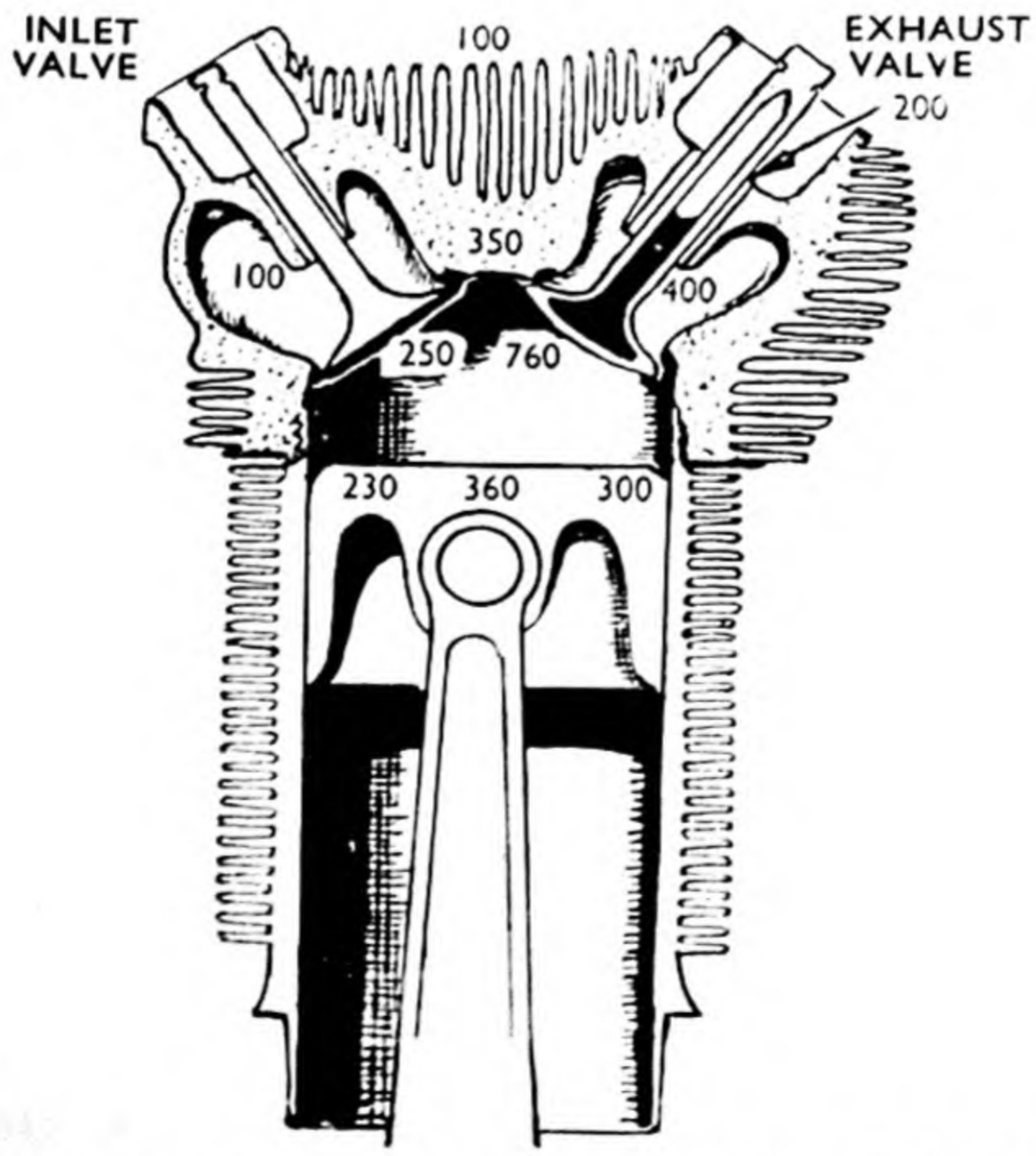


Fig. 49.—Mean working temperatures of an air-cooled engine cylinder in degrees centigrade

a sufficient area to the air to be left to look after itself, since it is not called upon to perform any exact mechanical operations; it is often red-hot when the engine is working and frequently "burns out". The exhaust valve also operates at dull-red heat, and would be even hotter but for the fact that special methods are employed to conduct the heat away. The valve stem is hollow and is partly filled with

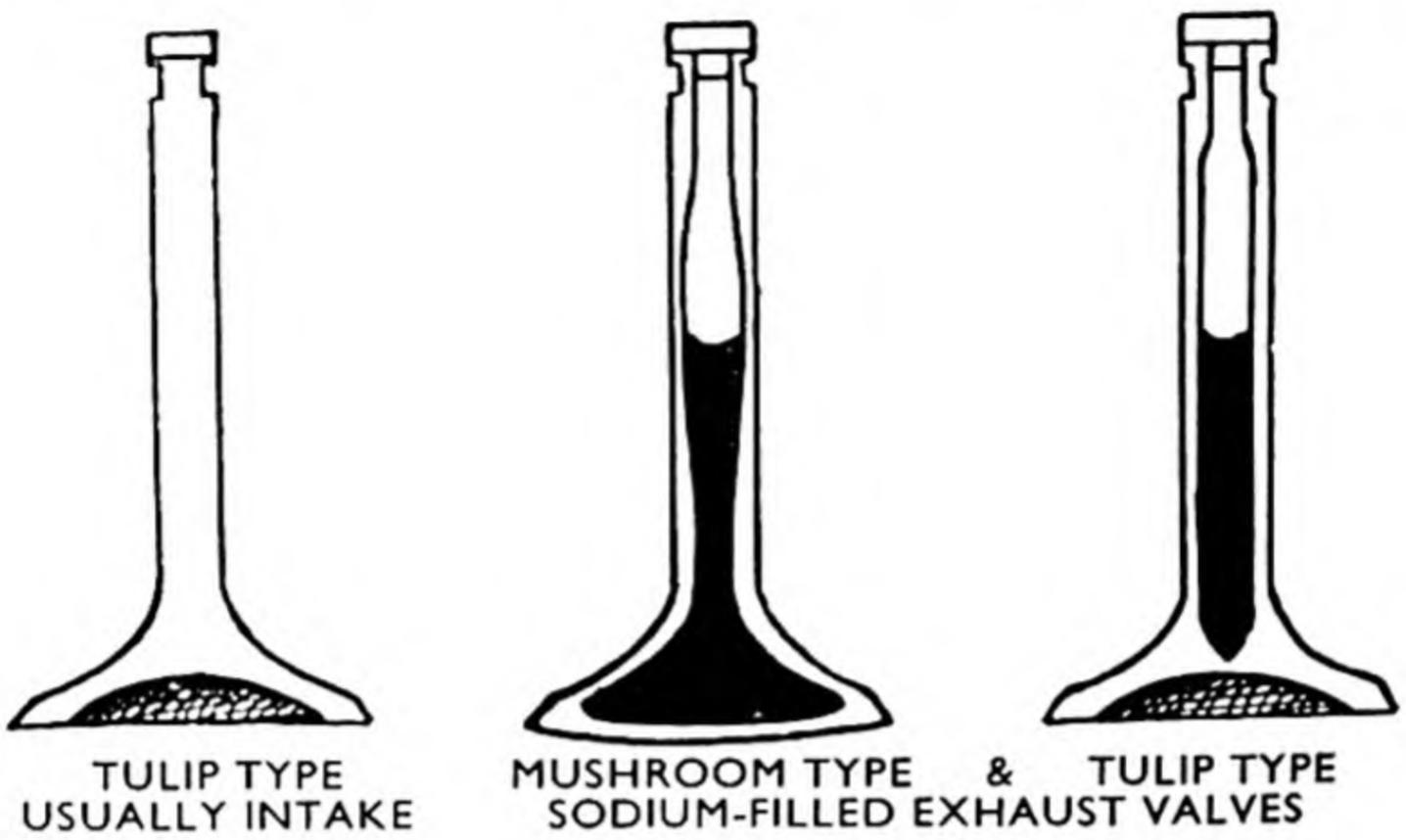


Fig. 50

sodium (see fig. 50). Sodium is an excellent conductor of heat. At operating temperatures it is molten, and as it is shaken violently up and down the space inside the valve stem, it conducts the heat to the valve guide and hence to the cooling fins. In a variation of this, the valve stem is entirely filled with solid copper, one of the best of heat conductors.

Methods of Air Cooling.

One of the difficulties associated with air cooling is the efficient cooling of those sides of the cylinders away from the air stream. Specially shaped sheets of metal, usually aluminium alloy, called baffle plates, lead the air where it is wanted, so that all parts of the cylinder are adequately cooled. Even so, it is difficult to provide sufficient air cooling for any but the smallest in-line engines, and bigger air-cooled engines are always radial, so that each cylinder receives the full force of the airstream. The baffle system of a small in-line engine is shown in fig. 51.

The cowling round an air-cooled engine is really part of the baffle system. It also greatly reduces the drag which would otherwise result from having a large radial engine at the front of the fuselage. In the bigger engines there are gills or shutters round the rear edge of the cowling, as in fig. 52. Since the drag that the cooling stream creates increases with its velocity, these shutters are kept nearly

closed in normal flight, so that the velocity of the airstream over the engine is just sufficient to maintain the correct engine temperature. On the ground, or during a steep climb, when the airstream has a reduced velocity or may consist only of the slipstream from the propeller, these gills are opened wide. It is, however, a good rule for any pilot not to run his engine on the ground for longer than necessary.

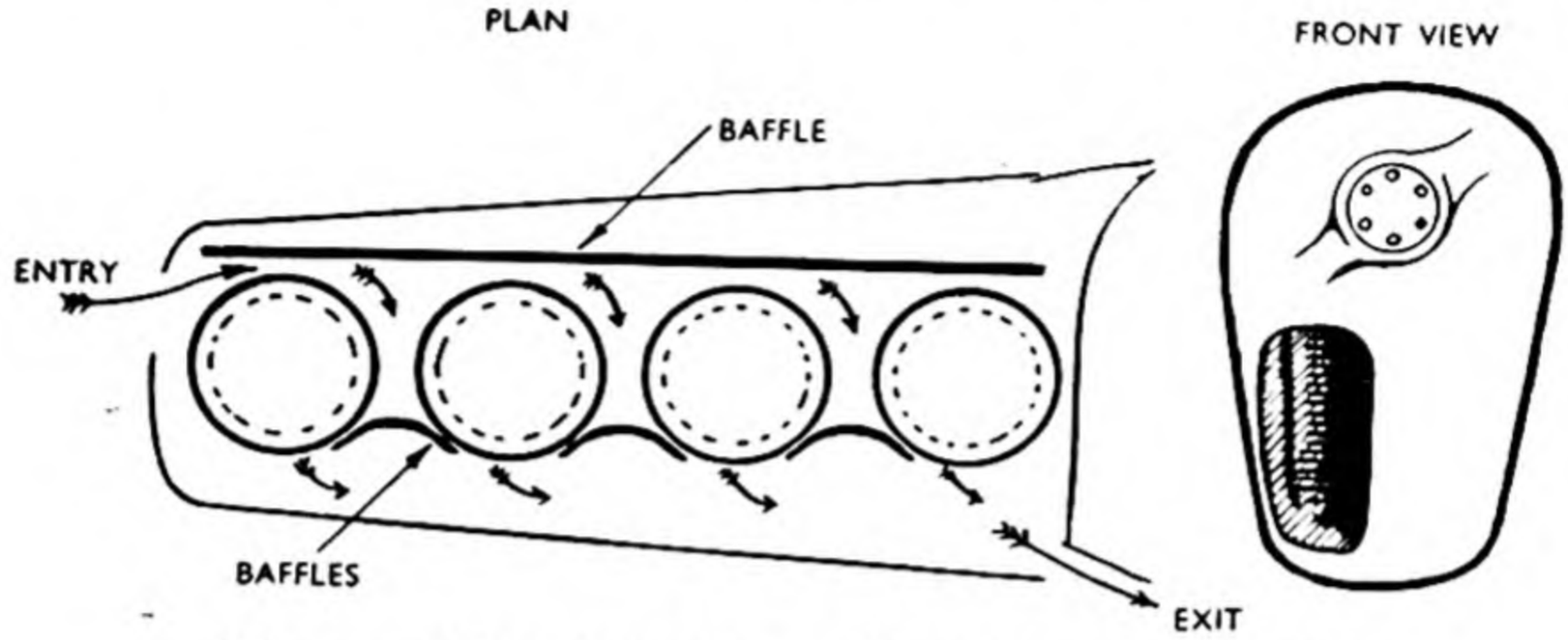


Fig. 51.—Air-cooling system of inverted in-line engine

These gills provide a measure of temperature control for the engine. Since the cowling plays such an important part in directing the airstream, the engine should never under any circumstances be run without it.

The cowling of the German B.M.W. 14-cylinder radial engine used on the Focke-Wulf 190 aircraft deserves special mention. It is a close-fitting low-drag cowling, with a central opening round the pro-

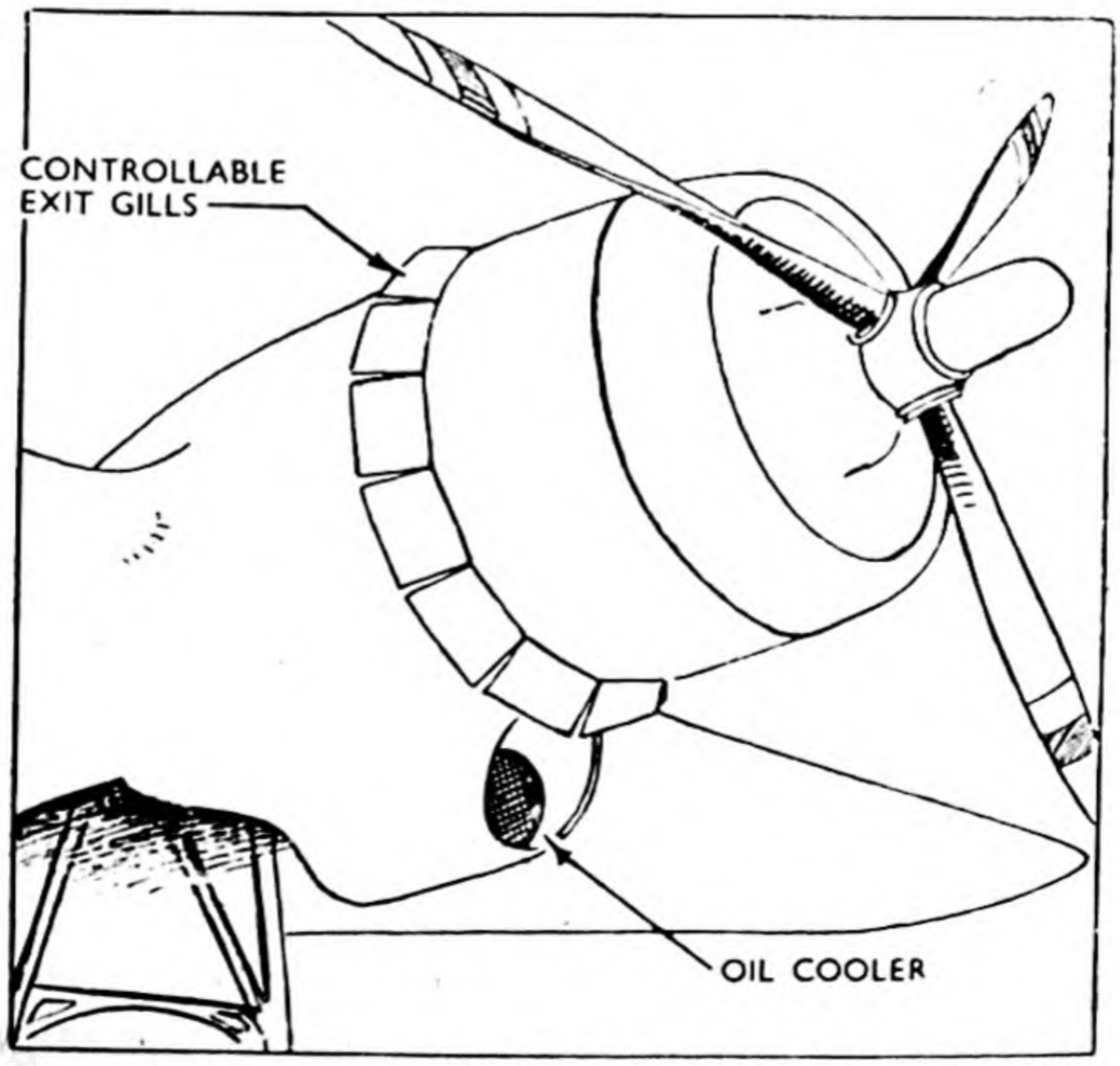


Fig. 52

peller hub. A 12-bladed fan, turning with about three times the crankshaft speed, is situated in the opening behind the propeller, and forces air past the engine. Forced cooling of this sort is an advantage when the aircraft engine is running on the ground, and at times when the full output of the engine is being called for at slow speeds, as in take-off and steep climb.

LIQUID COOLING

In this system a liquid called the coolant circulates through a jacket surrounding the cylinders, and the heat is removed as the coolant passes through a radiator exposed to the airstream. Both liquid and air cooling are fundamentally similar, for both transfer heat from the engine to the air. The liquid-cooling system, however, does so indirectly (fig. 53).

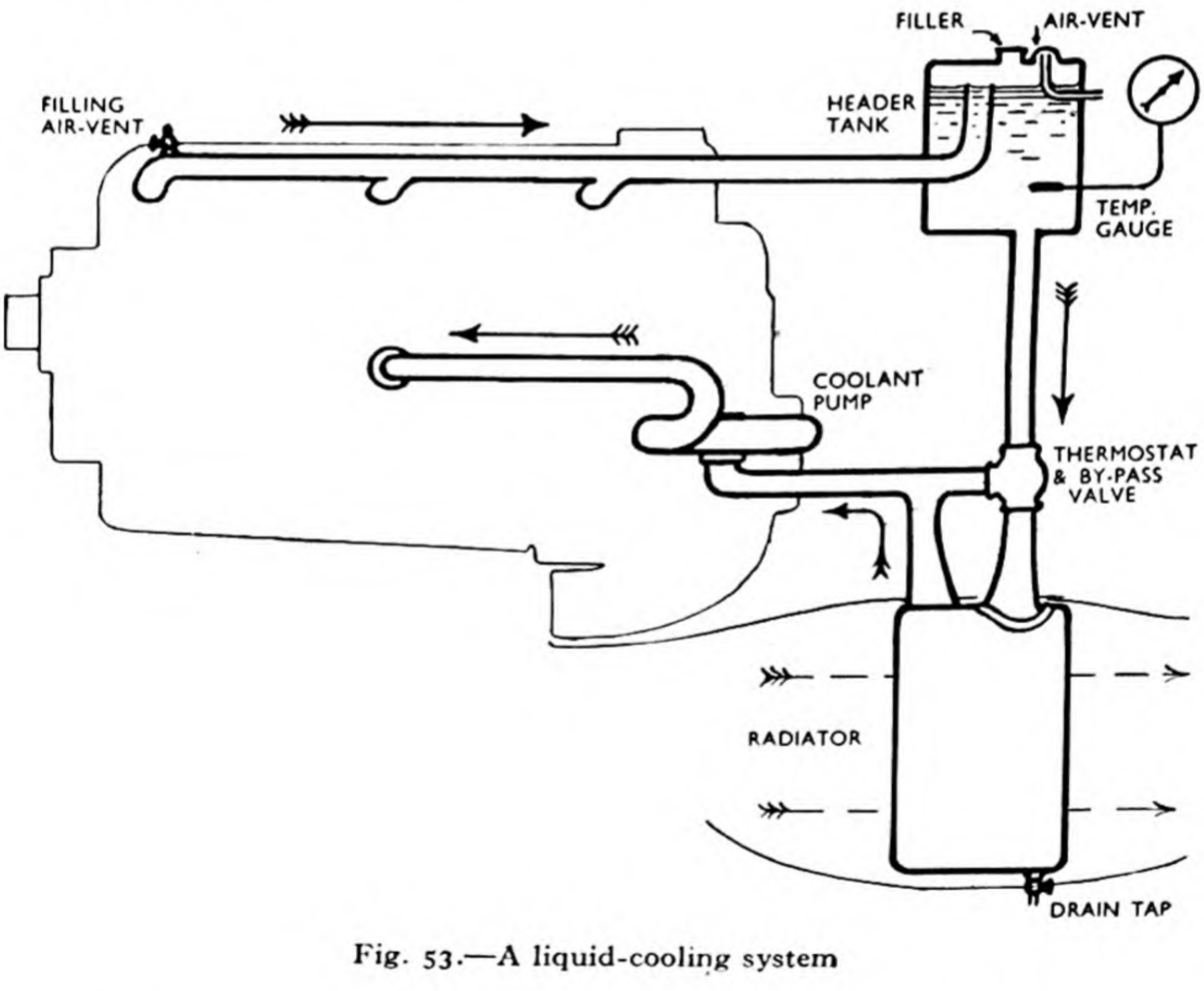


Fig. 53.—A liquid-cooling system

An engine-driven pump of a simple centrifugal type forces the coolant upwards through a single space between all the cylinders or "liners" of one bank and an outer aluminium alloy casting called the cylinder block. It then flows through channels surrounding the ports in the cylinder-head casting, and so leaves the engine to pass to a reservoir called the *header tank*. Adequate air space is left in the

tank for the very considerable expansion of the coolant when warmed, and the tank has a vent, or a relief valve, at the top The temperature of the hot coolant is measured in the tank by a thermometer that records in the pilot's cockpit.

From the bottom of the header tank the coolant is taken to the radiator (fig. 54), where it is cooled before being returned to the pump for recirculation. The coolant radiator is surrounded by a cowling or duct designed to reduce drag to the minimum, and the rate of flow of air through the radiator is limited by an adjustable flap or shutter at the rear of the duct to the minimum necessary for cooling. This flap is really an efficient means of temperature control, and it is often operated automatically under the control of a thermostat.

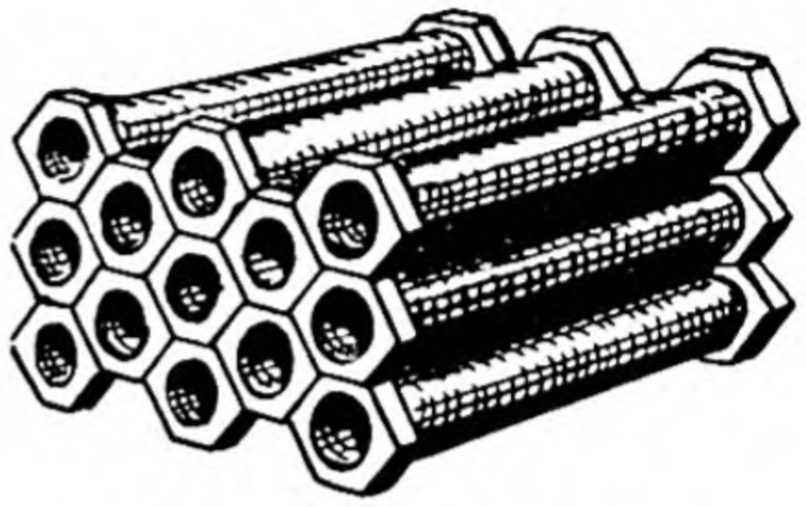


Fig. 54.—Part of a radiator

It is usual to house the oil and coolant radiators in a common duct, and though this is usually underneath the fuselage, as in fig. 55, in the Mosquito aircraft it is set in the leading edge of the wings between the engine and the fuselage.

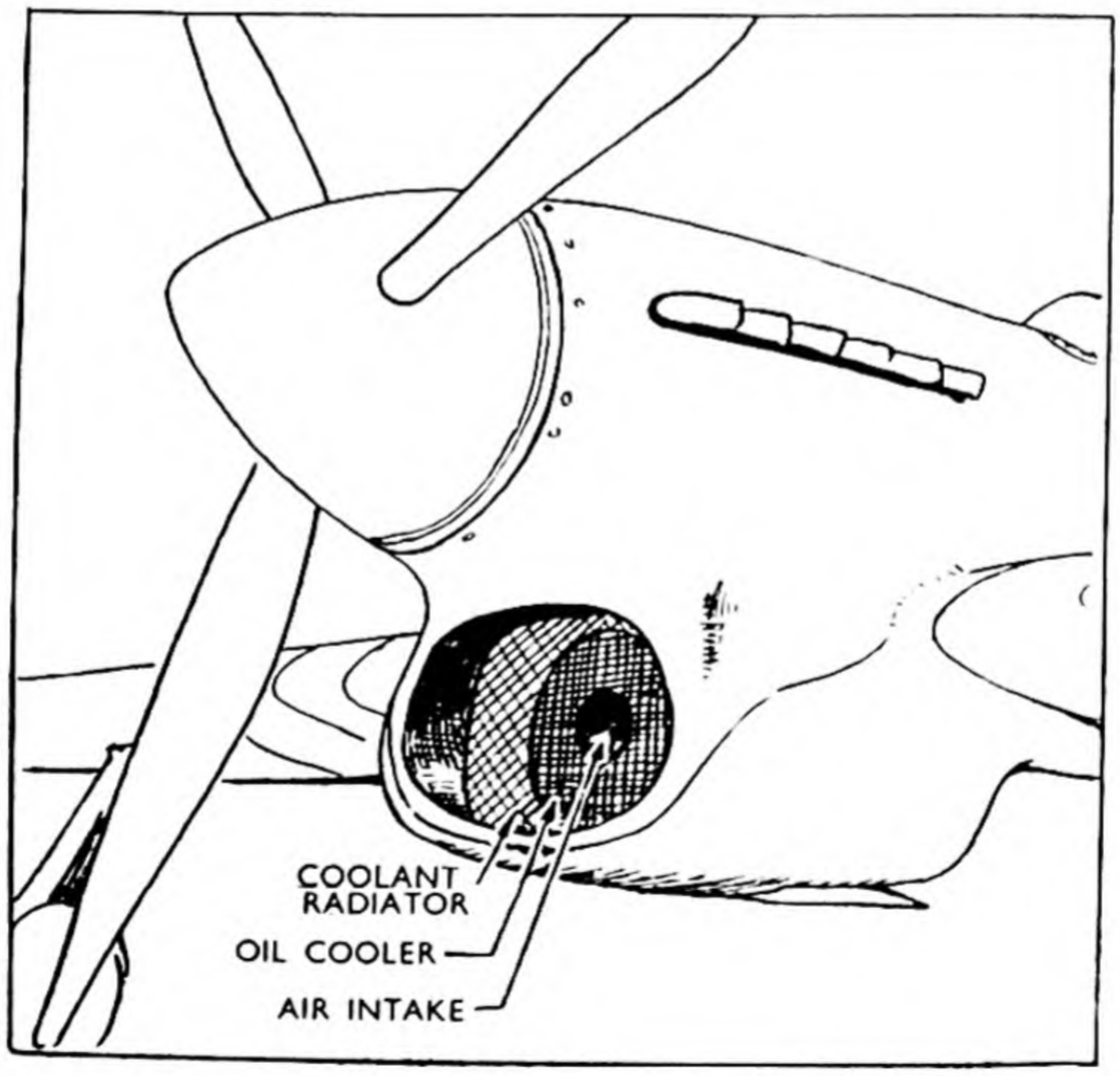


Fig. 55

Choice of Coolant.

Usually, nowadays, instead of water alone, a mixture of ethylene-glycol and water is used. The ethylene-glycol has a higher boiling-point and a lower freezing-point than pure water. The lower freezing-point is useful in cold weather, but the higher boiling-point offers two important advantages:

1. It allows the engine to operate at a higher temperature, and, at this higher temperature, it will have a greater thermal efficiency; that is, more of the heat will be turned to useful work.
2. The rate at which the radiator can reject heat is directly proportional to the temperature difference between it and its surroundings, so the higher operating temperature permissible enables the same quantity of heat to be dissipated with a smaller radiator. This, of course, reduces the drag of the aeroplane.

Sometimes the coolant is operated under pressure by having a spring-loaded valve at the vent in the header tank. This increase of pressure raises the boiling-point of the coolant still further.

Examples of liquid-cooled in-line engines include the famous Rolls-Royce Merlin series, the Allison and the Daimler-Benz D.B. 601 (all V-type in-line engines). The Napier Sabre is a 24-cylinder H-type liquid-cooled engine.

Choice of Cooling System.

1. *Weight.* In general, the two types of engine, air- and liquid-cooled, have about the same weight, so that the total weight of the liquid-cooled installation is heavier because of the weight of the cooling liquid, header tank, pipes, and extra radiator, a matter of 0·2 to 0·3 lb. per horse-power.

2. *Drag.* Here the liquid-cooled engine has its main advantage. The cylinders can be arranged in line to give a small frontal area and the radiator can be situated to the best advantage, whereas the arrangement of the larger air-cooled engine cylinder is radial, giving a large frontal area, and the cooling surface in the form of fins must be with the engine in a place where it creates most disturbance of the airstream.

3. *Maintenance and Reliability.* On this count the air-cooled engine obviously has the advantage. There is nothing much to go wrong.

4. *Vulnerability.* In war-time, the air-cooled engine has the advantage of being less easily put out of action, whereas the liquid-cooled engine is easily put out of action by damage to the cooling system.

There are, however, many other considerations, and it is impossible to say that one system is always better than the other.

QUESTIONS

1. (*a*) Give the two main differences between an ethylene-glycol and water mixture and water alone as coolants.

(*b*) What additional function does the coolant sometimes perform besides carrying away the heat from the engine?

(*c*) Give two advantages of the air-cooled engine over the liquid-cooled engine.

(*d*) Name, firstly, an air-cooled engine, and secondly, a liquid-cooled engine.

2. (*a*) Why are the cylinders of radial engines finned?

(*b*) How is the temperature of the cylinders of the radial engine controlled?

(*c*) What special method is employed to cool the exhaust valve?

(*d*) How are the bearings of the aero-engine cooled?

3. (*a*) Why may it be said that the two methods of cooling the engine, air and liquid, are essentially the same?

(*b*) Give one advantage of the liquid-cooling method over the air-cooling.

(*c*) Give two advantages of the air-cooling over the liquid-cooling.

4. (*a*) By what means is the expansion of the coolant when hot allowed for?

(*b*) What instrument is connected to the cooling system, and where is it connected?

5. (*a*) Why are baffle plates provided in the air-cooled engine?

(*b*) What is the purpose of the flaps or gills at the back of the radiator cowling?

(*c*) Under what condition of flight would they be fully open?

(*d*) About what percentage of the heat produced by the burning of the mixture is carried away by the cooling system in an aero-engine?

CHAPTER XVI

Alternatives: Two-stroke and Diesel Engines, Turbines, and Jet Propulsion

THE TWO-STROKE PETROL ENGINE. COMPRESSION-IGNITION (DIESEL) ENGINES. THE INTERNAL-COMBUSTION TURBINE. JET PROPULSION.

The four-stroke cycle internal-combustion petrol engine has been the sole subject for study so far, and this has been intentional, for almost without exception this is the engine used to propel the modern aircraft. It is not, however, the only type of heat engine. There are other ways of turning the energy of fuels into mechanical work, and other fuels. It is the purpose of this chapter to summarize some of the other heat engines that, from time to time, have been the subject of research with the object of using them in aircraft. Two of these are actually in use in successful flying machines, and one of them, the internal-combustion turbine, may very well be the aircraft engine of the future.

The Two-stroke Petrol Engine.

An engine operating on a two-stroke cycle has one working stroke out of two, double the number of a four-stroke engine, and, therefore, suggests itself as a means of obtaining double the power output without increase in size or weight of engine. Unfortunately, theory and practice disagree, and the four-stroke remains the engine with the best power-weight ratio.

The two-stroke engine is shown in section in fig. 56. In its simplest form it has no poppet valves. Inlet and exhaust ports in the side of the cylinder are covered and uncovered by the piston itself as it moves along the cylinder. As the piston approaches B.D.C. at the end of the power stroke the exhaust port is uncovered and the spent gases start to leave the combustion chamber. Almost immediately after, the inlet port to the cylinder is uncovered and fresh mixture flows in. The piston crown is usually shaped so as to deflect the new charge up into the cylinder head. Very soon after the piston has commenced its movement towards T.D.C. it covers both ports again. The charge is compressed, and just before T.D.C. the spark occurs, so that the

working stroke begins as the piston passes T.D.C. and moves along the cylinder.

In one simple form of two-stroke petrol engine the space behind the piston in the closed crankcase is used as a pump. The inlet from the carburettor enters at the cylinder base, so that when the long-skirted piston nears T.D.C. this inlet opens into the crankcase. Mixture then flows in to relieve the depression created there by the piston's withdrawal up the cylinder. As the piston returns, the inlet is covered and the charge compressed. The inlet port in the cylinder

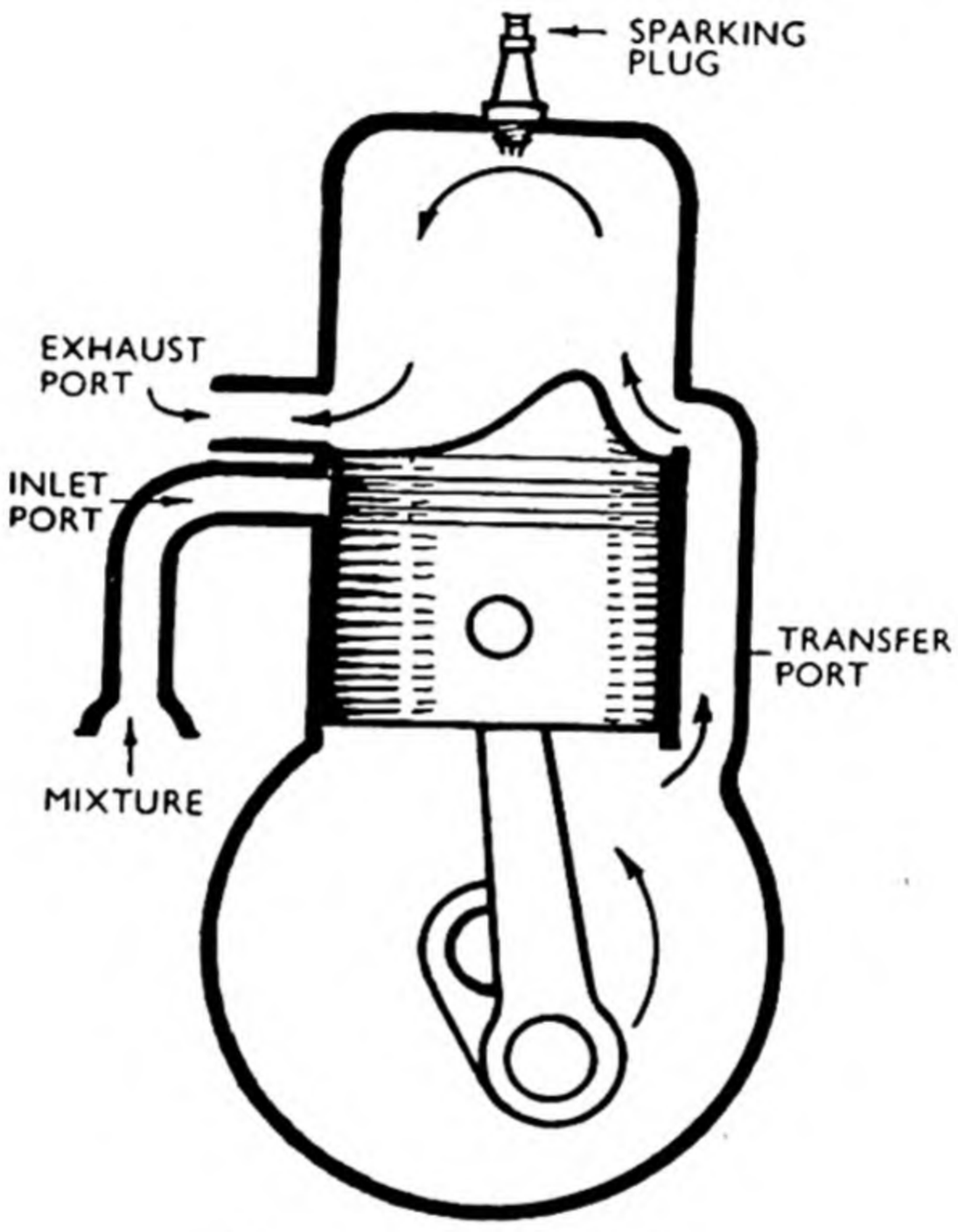


Fig. 56.—2-stroke engine

communicates only with the crankcase space and is properly termed a " transfer " port. By the time the transfer port is uncovered, the pressure of the charge in the crankcase is higher than atmospheric, whilst (owing to exhaust gas momentum) that in the cylinder is lower than atmospheric. Mixture, therefore, flows in through the transfer port.

Such an engine has the merit of simplicity, light weight, and small cost, and small two-stroke petrol engines have achieved a certain popularity in light motor-cycles, lawn-mowers, and small electric generator plants.

The disadvantages of the two-stroke engine are principally the following:

1. The high rate of working strokes presents a problem in engine cooling that is difficult to overcome with high-powered engines without an unusually heavy cooling system.
2. With both inlet and exhaust ports open together, it is difficult to avoid some intermingling of the incoming and outgoing gases. When the ports are covered, the cylinder contains a mixture diluted by exhaust gases. Less power is obtained from a two-stroke engine on this account than from an efficient four-stroke engine of similar size, in spite of the fact that the former has twice as many working strokes.
3. The two-stroke engine is wasteful in fuel, for it is impossible to prevent the escape of some of the fresh mixture through the open exhaust port. Small two-stroke engines of the kind described may allow 25 per cent of their fuel to leave the engine unburnt.

Compression-ignition (Diesel) Engines.

The essential feature of this form of the internal-combustion engine is the method used to ignite the mixture.

The heating of the charge during the compression stroke has been mentioned already (p. 106). The self-ignition temperature of heavy oil is much lower than that of petrol: heavy oil vapour will ignite spontaneously in air at about 350° C., whereas petrol, in spite of its greater volatility, requires a temperature of about 700° C. It is therefore not difficult, using heavy oil as a fuel, to arrange that the temperature at the end of the compression stroke shall be high enough to cause the fuel to ignite spontaneously. With such a method of firing the charge, pre-ignition is an obvious danger. This is prevented in the Diesel engine by feeding pure air into the cylinder during the induction stroke, and injecting the fuel only at the end of the stroke. The fuel is forced directly into the cylinder head in an atomized form by means of a pump, and ignites as it enters.

The engine may operate on either a two- or a four-stroke cycle.

The Diesel engine uses high compression ratios in order to vaporize the heavy oil and make sure that it ignites. Values of 12 to 1 and 15 to 1 are common. Pre-ignition cannot occur for the reason given above, and detonation may be avoided by proper control of the rate of entry of the fuel.

The influence of compression ratio on thermal efficiency has already been discussed. With such high compression ratios, the Diesel is a very efficient engine. Thermal efficiency may reach 42

per cent, as compared with 34 per cent, the best that can be hoped for with an ordinary petrol engine of compression ratio 7 to 1. The practical result of this is a *lower fuel consumption for a given power.* The compression-ignition engine makes better use of its fuel, and therefore uses less.

A Diesel engine does not deliver as much power from a given cylinder size as does an engine of normal compression ratio. Partly on this account and partly owing to the heavier construction that must accompany the high pressures which are used, the Diesel engine always weighs more than the commoner spark-ignition engine of comparable horse-power.

The Junkers firm of Germany manufacture a Diesel engine of interesting design that has been used in certain German long-range aircraft. The engine operates on the two-stroke cycle, and is unusual in that each cylinder has two pistons, working from opposite ends. The pistons move in and out together and are geared externally to a common propeller shaft. Oil is sprayed into the cylinder through several nozzles situated half-way along the cylinder. The pistons are driven apart during the power stroke, and towards the end of their travel exhaust ports are uncovered at one end. Scavenging is completed when, very soon after, the other piston uncovers the air inlet ports, and air under pressure drives the remaining spent gases before it along the cylinder. It is interesting to note that loss of fuel during intake, which is usually one of the faults of the two-stroke engine, is here avoided by the use of air alone to clear the spent charge from the cylinders.

A late design of the Junkers' Jumo series, the 206, of 1000 h.p., weighs 1·4 lb. per horse-power as compared with the value of slightly under 1 lb. per horse-power that has been attained with the best spark-ignition engines. The fuel consumption is about 20 per cent lower than that with spark-ignition engines using high-octane fuel.

The advantages of the compression-ignition engine for aircraft purposes may be summarized as follows:

1. Less risk of fire.
2. Cheaper fuel.
3. Lower fuel consumption per horse-power hour.
4. No need for carburettors or magnetos.

The main disadvantage lies in its greater weight per horse-power.

The Internal-combustion Turbine.

Turbines represent as a class the most promising alternative to the reciprocating engine as a means for turning heat to work. Steam turbines have successfully challenged piston-operated steam engines for heavy marine engines, and are widely employed as the driving mechanism of electric generating plants.

The steam turbine works in the following manner. The steam is generated in a boiler, separated usually for convenience from the turbine itself, and conducted through insulated pipes to the turbine, where it issues at very high speed from a set of nozzles. The jets of steam impinge on the cup-shaped blades of the rotor, which is thus made to revolve at high speed. The direction of the steam jets is almost reversed as they rebound from the rotor blades, but by allowing the steam to strike similarly shaped blades of a fixed stator, its direction is reversed a second time, and it may be made to strike a second ring of blades on the rotor shaft. This is repeated a number of times, the steam rebounding from rotor to stator blades in turn as it passes axially along the turbine. It is the change in momentum of the working substance each time its direction is reversed that provides the force to drive the turbine round, and the energy given up by the steam causes its continual fall in temperature.

Such an engine has the merits of lightness, simplicity and compact design, but, equally important, it is more efficient than a reciprocating engine of the same power. The trouble of perfectly balancing the moving parts in order to avoid vibration—a very real difficulty with the reciprocating engine—is overcome much more easily with the smooth continuous rotation of the turbine rotor. The disadvantage of the turbine, for some purposes, lies in the fact that, for efficient operation, it should work within a narrow range of very high speeds, and gearing therefore presents something of a problem.

Advantages similar to those of the steam turbine might confidently be claimed for the internal-combustion turbine using petrol, paraffin or heavy oil. Until recently, however, the only engine of this type in use was a 20,000-h.p. turbine belonging to the Swiss Railways. Successful small turbines of this type have now been manufactured in America for turbo-superchargers, and in England for the jet-propelled aircraft.

The turbine aero-engine comprises three units: a supercharger or compressor, a chamber in which the fuel mixture is burnt, and the turbine proper. The compressor rotor and the turbine rotor are built on to a common shaft. The greater simplicity of this arrangement,

when compared with the comparatively cumbersome collection of pistons, valves, valve-operating mechanism, connecting rods and cranks associated with the more usual type of engine, is at once apparent.

Once started, the compressor pumps air into the combustion chamber. The liquid fuel is injected directly into the compressed air as a fine spray, after the manner of the direct-injection system of some reciprocating engines, and continuous burning results. The hot gases, greatly increased in volume, are then passed to the turbine unit. There is no valve system to isolate the compressor from the combustion chamber, so that the pressure in this part of the engine can never be higher than at the compressor outlet. Since, therefore, pressures as high as occur in the reciprocating unit are not met with in the turbine, problems of detonation do not arise. This means that fuels much cheaper than the high-octane spirit necessary for the usual aero-engine can be used—another advantage for the turbine.

Lastly, the shape and small size of the compressor turbine unit lends itself admirably to streamlining.

It may well be that the light, simple, compact internal-combustion turbine, using cheap fuel, will become the aero-engine of the future.

JET PROPULSION

The advent of the jet-propelled aircraft seems to be the most revolutionary of all recent developments in new ways of propelling and supporting heavier-than-air machines, inasmuch as it dispenses entirely with the propeller for obtaining forward thrust.

Fundamentally, however, all methods of providing a forward thrust depend on the same principle, namely, in a fluid reaction obtained from the continuous throwing of a mass of substance backwards. In the case of the propeller-driven aircraft air is thrown back by the propeller; in the case of the jet-propelled aircraft air, or more strictly the products of combustion (which exceed the weight of air by the comparatively small additional weight of the fuel), are ejected backwards to fulfil the same purpose.

To impart momentum to a mass of air requires a force. If air is continuously ejected a continuous force is necessary. The aircraft cannot apply this force to the mass of air without experiencing an equal reaction itself. This reaction is the forward thrust (see fig. 57).

An analogy may help to clarify this for the reader who is unfamiliar with Newton's fundamental laws of motion. A gun recoils when the shot is fired, because the gun experiences just as great a force in one direction as the gases and the bullet together experience in the other.

Imagine the gun free to move on wheels, and a rapid succession of bullets being fired. Each shot would impart some additional backward speed to the gun, until, when retarding frictional forces from the wheels and drag of the air had increased sufficiently with increase in speed, the gun would cease accelerating and move with a constant speed. The recoil action (or reaction) of the bullets would, if suffi-

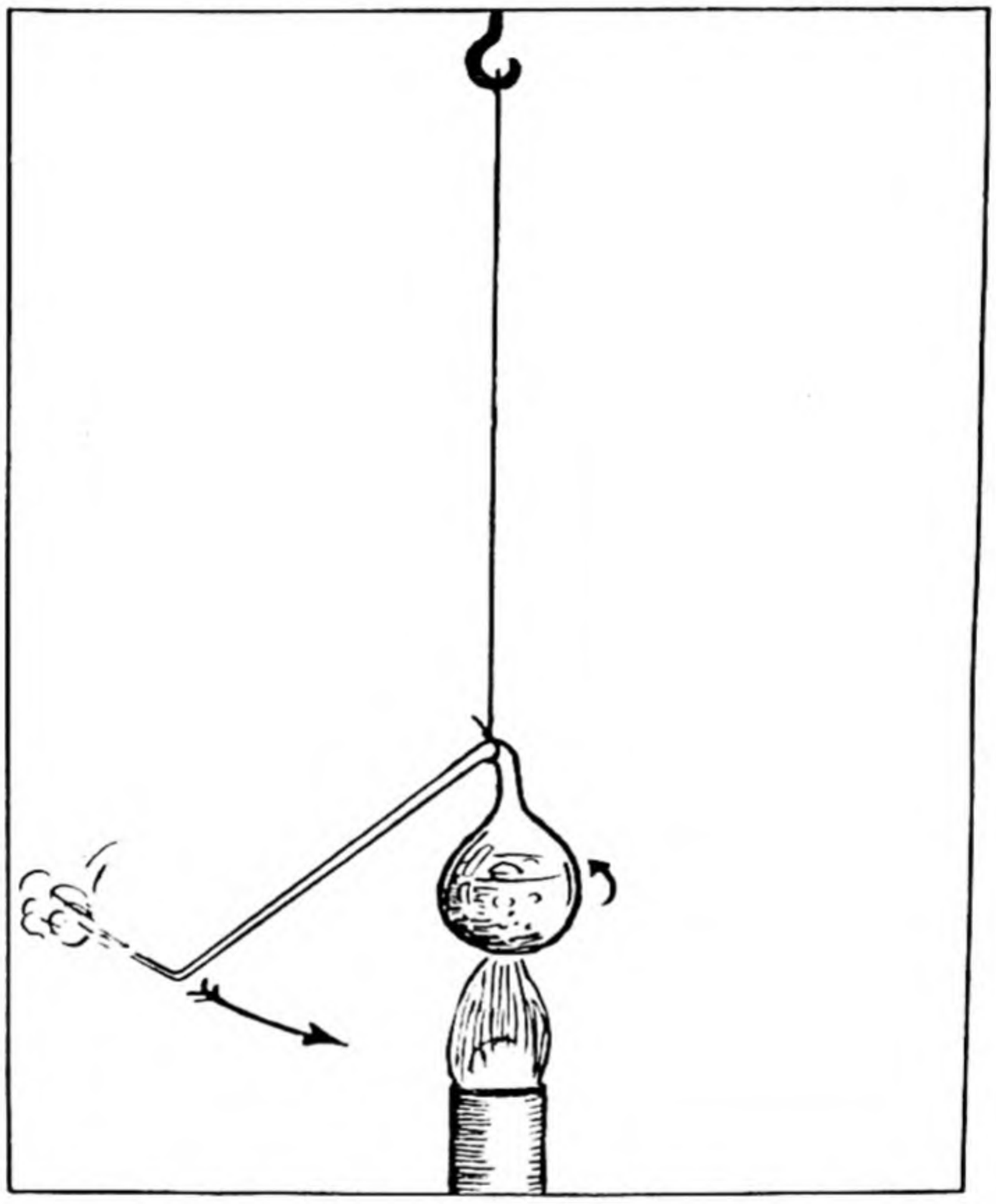


Fig. 57.—A simple experiment, showing the principle of jet propulsion. The " engine " is constructed from a glass test-tube

ciently rapid, now be exerting a continuous steady force on the gun equal to the drag forces opposing its motion.

In the aircraft the air that is thrown back takes the place of the bullets, and the aircraft of the gun. When the thrust due to reaction from the mass of air ejected is equal to the drag, the aircraft will proceed at a steady speed.

Notice that it makes no difference whether the bullets strike a brick wall or not, and with similar reasoning it should be clear that the aircraft does not maintain its forward speed because the gases ejected push on a " wall of surrounding air ". The method of obtaining forward thrust is equally effective in a vacuum, provided that something can be thrown back. In other words, there is no difference in this

respect between "rocket" and "jet" propulsion. Rocket projectiles, too, obtain forward speed from the reaction due to ejecting backwards products of combustion of definite mass.

The compressor-turbine unit (fig. 58) is particularly well adapted for jet propulsion. The absence of a propeller eliminates all gears, and the high speed of the rotor presents no difficulty. If the compressor is enlarged, relative to the turbine, a great mass of air can be driven through the unit, and, instead of the turbine working against a propeller load, the available energy may be used to impart energy of motion directly to the aircraft and the gases that are exhausted from the rear of the unit. When the engine is used to drive a propeller, energy of motion in the exhaust gases can generally be regarded as

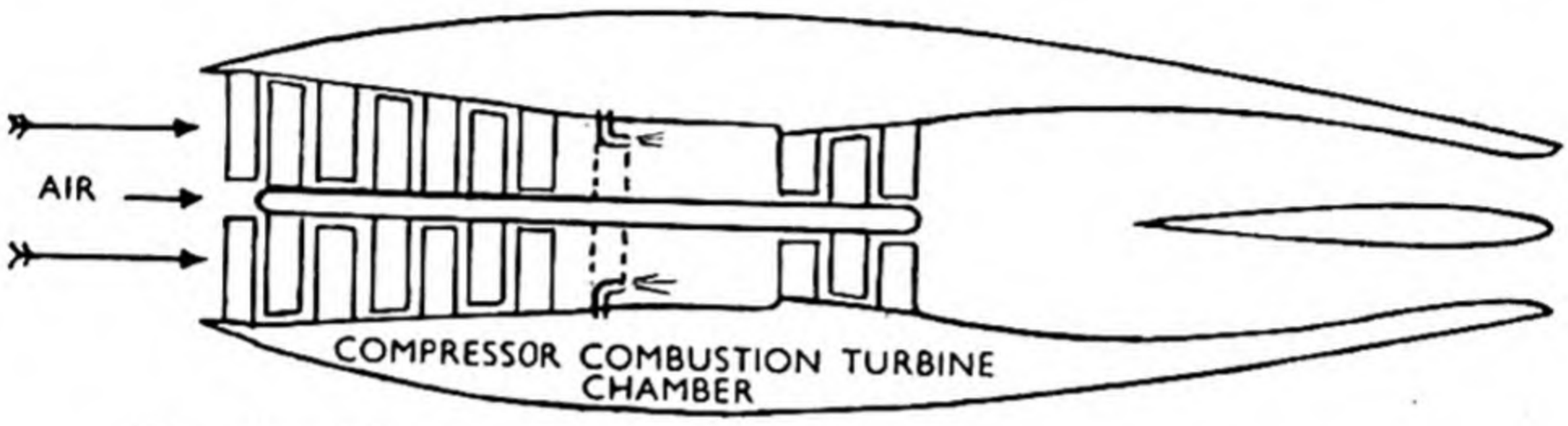


Fig. 58.—Schematic layout of a turbine-operated jet-propulsion unit

waste, but when the engine is used to drive air from the aircraft directly, the more energy of motion obtained the better.

This needs some qualification. The heat energy of the fuel, as with the reciprocating engine, may be dissipated in several ways: some will be used in working against the forces of friction; some will remain as heat energy in the exhausted gases; the remainder will be shared between the moving aircraft and the moving gases. The thermal efficiency of the engine may be assessed on the ratio of energy of motion given to the aircraft and air to the total heat content of the fuel, and it is clear that, as with the reciprocating engine, the cooler the exhausted gases are when they finally leave the jet, the more efficient the engine will be.

The efficiency of the jet as a means of propulsion is another matter, and is analogous to the efficiency of the propeller in the usual type of aircraft. This depends on how much of the mechanical energy is successfully transferred to the aircraft, and how much is lost in the slipstream or jet. In the parallel case of the gun and the bullets, by far the greater share of the energy from the explosive charges is transferred to the bullets, and a very small remainder is absorbed by the gun. If, therefore, the object were to propel the gun, the device would be considered very inefficient, but if, as is actually the case,

interest is centred on the speed of the bullets, the method of achieving the desired result would be considered highly efficient. Now why is this so? It may be shown that the sharing of the available energy depends on the ratio of the masses of the bullets and the gun. The lighter object absorbs more of the energy. Therefore, the heavier the gun relative to the bullets, the smaller will be the energy absorbed by the recoil, and the greater will be the energy, and therefore speed, of the bullets.

In the same way the necessary forward speed of the aircraft may be maintained by throwing back a small mass of air with a large velocity, or a large mass of air with a small velocity; but both are not equally efficient, and if a large mass of air of low velocity is used a greater proportion of the energy is given to the aircraft, and less is lost in the stream of air that is left behind. A simple mathematical proof of this is given in the Appendix for readers who are interested in it.

Unless, then, the jet orifice has as large a diameter as the propeller, the latter will always be able to deal with a greater volume of air than the jet, at equal slipstream and jet velocities, and unless the air from the jet is denser, owing to high pressure or low temperature, the propeller will therefore affect a greater mass of air per second. For this reason the jet will generally be less efficient than the propeller at normal speeds. At very high speeds the propeller efficiency cannot be maintained, and then the jet comes into its own. At high altitudes high speeds are necessary to give sufficient lift in the low-density air; moreover, the low density reduces drag and makes high speeds possible, *provided that the efficiency of the propelling mechanism can be maintained.* It has been pointed out that there is a limit to the speeds at which a propeller can be used effectively, and it therefore follows that *at high altitudes the advantage lies with the jet.* It may be expected that jet propulsion will therefore find its most useful application in aircraft fitted with pressure cabins and designed to fly at very high altitudes and high speeds.

Many other points must be considered to gain a comprehensive picture of the " pros and cons " of this new type of aircraft. In the first place, it must be kept in mind that it is the overall efficiency of the whole system that really counts. Moreover, ultimate speed depends on drag, and the turbine-jet system is particularly well adapted to good streamlining. It is no small matter to be rid of the buffeting of the slipstream; whatever engine is adopted, the weight will be less by the weight of the propeller and its gears; and finally, since ground clearance of a large-diameter propeller is not necessary with the jet, smaller and lighter undercarriages are possible.

APPENDIX

Proof of Efficiency Formula for Jet

Let the aircraft be flying at constant speed in level flight.

$$\text{Thrust} = \text{Drag } (D). \quad . \quad . \quad . \quad . \quad (1)$$

Let a mass (m) of gas be ejected backwards along the line of flight per unit time with a velocity (v), and let V be the velocity of the aircraft, both velocities being measured relative to surrounding still air.

Then, from Newton's law, " the rate of change of momentum is proportional to the impressed force, and takes place along the line of action of the force ", we have:

$$\text{Force exerted on gases} = mv.$$

From Newton's law, " action and reaction are equal and opposite ", it is clear that this is the force on the aircraft, i.e. D.

$$D = mv. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Work done per unit time by the aircraft

$$= DV = mvV.$$

Now efficiency of jet

$$= \frac{\text{Work done by aircraft per unit time}}{\text{Total mechanical energy supplied by engine}} \times 100 \text{ per cent}$$

$$= \frac{\text{Work done by aircraft per unit time}}{\text{Work done by aircraft per unit time} + \text{energy given to gases per unit time}} \times 100 \text{ per cent}$$

$$= \frac{mvV}{mvV + \frac{1}{2}mv^2} \times 100 \text{ per cent}$$

$$= \frac{2}{2 + \frac{v}{V}} \times 100 \text{ per cent.}$$

From this it is clear that the lower the velocity of the ejected gases relative to the aircraft's velocity, the nearer the efficiency is to 100 per cent.

If v is small, then, from equation (2), at a given speed the ejected mass per unit time must be large. Hence it is better to eject a large mass at low speed than a small mass at high speed.

ANSWERS TO NUMERICAL EXAMPLES

Chap. I.	12.	(*a*) 9. (*b*) $\frac{1}{3}$ lb. per square foot.
III.	6.	100 lb.
	7.	Decrease by 67 lb. approx.
	8.	(*a*) Drag. (*b*) 6.
	9.	Lift 14,210 lb.: download of 210 lb. on tail.
	10.	Upload of 278 lb. approx.
Chap. X.	3.	28·3 per cent.
	4.	1·8 lb. per minute approx.

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